NASA-TM-108652

OAET

SSTAC/ARTS REVIEW OF THE DRAFT INTEGRATED TECHNOLOGY PLAN (ITP)

Volume III: June 26-27

Space Power & Thermal Management

Briefings from the
June 24-28, 1991 Meeting
McLean, Virginia

National Aeronautics and Space Administration
Office of Aeronautics, Exploration and Technology
Washington, D.C. 20546

(NASA-TM-108652) SSTAC/ARTS REVIEW OF THE DRAFT INTEGRATED TECHNOLOGY PLAN (ITP). VOLUME 3: SPACE POWER AND THERMAL MANAGEMENT (NASA) 321 p

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Unclas

G3/81 0150609

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SSTAC/ARTS REVIEW OF THE DRAFT ITP
McLean, Virginia
June 24-28, 1991

Volume III: June 26-27

Space Power & Thermal Management

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Space Energy Conversion Research and Technology

INTEGRATED TECHNOLOGY PLAN
EXTERNAL REVIEW
26 JUNE 1991

Gary L. Bennett
Manager, Advanced Space Power Systems
Propulsion, Power and Energy Division
Office of Aeronautics, Exploration and Technology
NASA Headquarters

AGENDA
POWER AND THERMAL MANAGEMENT
DISCIPLINE REVIEW

WEDNESDAY, JUNE 26, 1991

8:30 AM	ADMINISTRATORS REMARKS	R. Truly
9:30 AM	POWER OVERVIEW (90 min.)	G. Bennett
	R&T BASE:	
11:00 AM	PHOTOVOLTAICS (45 min.)	D. Flood
11:45 AM	CHEM. ENERGY CONVERSION (45 min.)	P. Bankston
12:30 PM	LUNCH (60 min.)	All
1:30 PM	THERMAL ENERGY CONVERSION (60 min.)	P. Bankston/ Calogeras
2:30 PM	POWER MANAGEMENT (90 min.)	Bercaw/W. Meador
4:00 PM	THERMAL MANAGEMENT (45 min.)	Swanson
4:45 PM	ADJOURN	

THURSDAY, JUNE 27, 1991

	FOCUSED TECHNOLOGY:	
8:00 AM	SPACE NUCLEAR POWER (60 min.)	J. Sovie
9:00 AM	HIGH CAPACITY POWER (60 min.)	J. Sovie
10:00 AM	SURFACE POWER & TM (45 min.)	J. Bozek
10:45 AM	EARTH-ORBIT PLAT. POWER & TM (45 min.)	R. Cull
11:30 PM	LASER POWER BEAMING (45 min.)	J. Rather
12:15 PM	LUNCH (60 min.)	All

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ORDER OF PRESENTATION MATERIAL

- Work Breakdown Structure
- Space Power Technology
- Integrated Technology Plan Process
- Space Power Background
- Technology Needs
- Space Power Reviews and Studies
- Space Power Technology Development
- Coördination and Interfaces
- Budgets
- Summary
- External Review Process

Work Breakdown Structure

PROPULSION, POWER & ENERGY DIVISION

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SPACE PROGRAM ELEMENTS

PROPULSION

R&T BASE
- LOW THRUST (WATKINS)
- ADVANCED PROPULSION CONCEPTS (WATKINS)
- HIGH THRUST CHEMICAL (ESCHER)
- CRYO FLUID MGMT (WATKINS)

CSTI PROGRAM
- EARTH-TO-ORBIT (ESCHER)

EXPLORATION TECHNOLOGY
- SPACE BASED ENGINES (ESCHER)
- CRYO. FLUID SYSTEMS (WATKINS)
- NUCLEAR PROPULSION (BENNETT)

POWER

(BENNETT)

R&T BASE
- PHOTOVOLTAIC ENERGY CONVERSION
- CHEMICAL ENERGY CONVERSION
- THERMAL ENERGY CONVERSION
- POWER MANAGEMENT
- THERMAL MANAGEMENT

CSTI PROGRAM
- HIGH-CAPACITY POWER

EXPLORATION TECHNOLOGY
- SPACE NUCLEAR POWER
- SURFACE SOLAR POWER

LIFE SUPPORT SYSTEMS

(EVANICH)

R&T BASE
- HUMAN SUPPORT PROGRAM (W/CODE RC - JENKINS)

EXPLORATION TECHNOLOGY
- REGENERATIVE LIFE SUPPORT

FY 1991

INTEGRATED TECHNOLOGY PLAN FOR THE CIVIL SPACE PROGRAM

WORK BREAKDOWN STRUCTURE

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RESEARCH AND TECHNOLOGY BASE

DISICPLINE RESEARCH
- Aerothermodynamics R&T
- Space Energy Conversion R&T
- Propulsion R&T
- Materials & Structures R&T
- Information & Controls R&T
- Human Support R&T
- Advanced Communications R&T

UNIVERSITY PROGRAMS
- University Research

SPACE FLIGHT R&T
- Flight Experiment Studies
- IN-STEP

SYSTEMS ANALYSIS
- Systems Analysis

MAY 16, 1991
JCM-7209

WORK BREAKDOWN STRUCTURE

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CIVIL SPACE TECHNOLOGY PROGRAM

- **SPACE SCIENCE**
  - Science Sensing
  - Observatory Systems
  - In Situ Science
  - Science Information
  - Technology Flight Experiments
- **SPACE EXPLORATION**
  - Surface Systems
  - Exploration Human Support
  - Technology Flight Experiments
- **TRANSPORTATION**
  - Earth-to-Orbit Transportation
  - Space Transportation
  - Technology Flight Experiments
- **SPACE PLATFORMS**
  - Earth-Orbiting Platforms
  - Space Stations
  - Deep-space Platforms
  - Technology Flight Experiments
- **OPERATIONS**
  - Space A&R
  - Infrastructure Operations
  - Information & Communications
  - Technology Flight Experiments

MAY 17, 1991
JCM 7208a

NASA

EXPLORATION TECHNOLOGY

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WORK BREAKDOWN STRUCTURE

EXPLORATION TECHNOLOGY PROGRAM

- **INNOVATIVE TECHNOLOGIES & SYSTEMS ANALYSIS**
  - Innovative Technologies
  - Exploration Systems Analysis
- **SPACE TRANSPORTATION**
  - Space-Based Engines
  - Aerobraking
  - Autonomous Vehicle Maneuvering
  - Structures & Cryogenic Tanks
  - Artificial Gravity
- **HUMAN SUPPORT**
  - Regen Life Support
  - Radiation Protection
  - EVA Systems
  - Exploration Human Factors
- **SURFACE OPERATIONS**
  - Space Nuclear Power
  - Surface Solar Power
  - Planetary Rover
  - In Situ Resource Utilization
  - Surface Habitats & Construction
- **IN-SPACE OPERATIONS**
  - Cryo Fluid Sys
  - In-Space Assy & Construction
  - Vehicle Servicing & Processing
- **INFORMATION SYSTEMS & AUTOMATION**
  - High-Rate Communications
  - Remote Surface/Science Operations
  - Planetary Photonics
  - Exploration Data Systems
- **LUNAR & MARS SCIENCE**
  - Sample Acq., Analysis & Preserv
  - Planetary Probes & Penetrators
  - Astrophysics Observatories
- **NUCLEAR PROPULSION**
  - Nuclear Thermal Propulsion
  - Nuclear Electric Propulsion

FY 90 - 91 PROGRAM CHANGES

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PATHFINDER

SURFACE EXPLORATION

- Surface Power
- Planetary Rover
- Sample Acquistion, Analysis & Preservation
- Autonomous Lander
- Photonics

IN-SPACE OPERATIONS

- Space Nuclear Power (SP-100)
- Autonomous Rendezvous & Docking
- In-Space Assembly & Construction
- Cryogenic Fluid Depot
- Resource Processing Pilot.
- Optical Communications

EXPLORATION TECHNOLOGY

SURFACE OPERATIONS

- Space Nuclear Power
- Surface Solar Power
- Planetary Rover
- In Situ Resource Utilization
- Surface Habitats & Construction

REVISED WORK BREAKDOWN STRUCTURE

OAET

- SPACE R&T BASE
- IN-SPACE TECH. EXPER. PROG.

→

- SPACE R&T BASE

- CSTI PROGRAM
  - SCIENCE
  - TRANSPORTATION
  - OPERATIONS
- EXPLORATION TECHNOLOGY
  - SPACE TRANSPORTATION
  - IN-SPACE OPERATIONS
  - SURFACE OPERATIONS
  - HUMAN SUPPORT
  - LUNAR & MARS SCIENCE
  - NUCLEAR PROPULSION
- SPACE AUTOMATION & TELEROBOTICS

→

- CIVIL SPACE TECHNOLOGY PROGRAM
  - SPACE SCIENCE TECHNOLOGY
  - TRANSPORTATION TECHNOLOGY
  - OPERATIONS TECHNOLOGY
  - SPACE EXPLORATION TECHNOLOGY
  - SPACE PLATFORMS TECHNOLOGY

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REVISED WORK BREAKDOWN STRUCTURE

OAET

- SPACE R&T BASE
  - Aerothermodynamics
  - Space Energy Conversion
  - Propulsion
  - Materials & Structures
  - Space Flight
  - Systems Analysis
  - University Space Research
  - Information and Controls
  - Human Support
- IN-SPACE TECH. EXPER. PROG.
- CSTI PROGRAM
  - SCIENCE
    - Science Sensor
    - High Rate/Capacity Data Systems
    - Precision Segmented Reflectors
  - TRANSPORTATION
    - Earth to Orbit
  - OPERATIONS
    - Telerobotics
    - Artificial Intelligence
    - High Capacity Power
    - Controls/Structures Interaction
- EXPLORATION TECHNOLOGY
  - SPACE TRANSPORTATION
    - Aerobraking
    - Space Based Engines
    - Autonomous Landing
    - Autonomous Rendezvous & Docking
  - IN-SPACE OPERATIONS
    - Cryogenic Fluid Systems
    - In-Space Assembly and Construction
  - SURFACE OPERATIONS
    - Space Nuclear Power
    - In-Situ Resource Utilization
  - HUMAN SUPPORT
    - Regenerative Life Support
    - Radiation Protection
    - Extravehicular Activities Systems (Surface)
    - Exploration Human Factors
  - LUNAR & MARS SCIENCE
    - Sample Acquisition, Analysis & Preservation
    - Planetary Probes & Penetrators
  - NUCLEAR PROPULSION
    - Nuclear Thermal Propulsion
  - INNOVATIVE TECHNOLOGY
    - Exploration Technology Analysis
- SPACE AUTOMATION & TELEROBOTICS
- AEROASSIST FLIGHT EXPERIMENT

→

- SPACE R&T BASE
  - Discipline Research
    - Aerothermodynamics
    - Space Energy Conversion
    - Propulsion
    - Materials & Structures
    - Information and Controls
    - Human Support
    - Adv. Communications
  - University Programs
  - Space Flight R&T
    - Flight Experiment Studies
    - IN-STEP
  - Systems Analysis
- CIVIL SPACE TECHNOLOGY PROGRAM
  - SPACE SCIENCE TECHNOLOGY
    - Science Sensing
    - Observatory Systems
    - Science Information
    - In Situ Science
    - Technology Flight Expts.
  - TRANSPORTATION TECHNOLOGY
    - ETO Transportation
    - Space Transportation
    - Technology Flight Expts.
  - OPERATIONS TECHNOLOGY
    - Automation & Robotics
    - Infrastructure Operations
    - Info. & Communications
    - Technology Flight Expts.
  - SPACE EXPLORATION TECHNOLOGY
    - Surface Systems
    - Human Support
    - Technology Flight Expts.
  - SPACE PLATFORMS TECHNOLOGY
    - Earth-Orbiting Platforms
    - Space Stations
    - Deep-Space Platforms
    - Technology Flight Expts.

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Space Power Technology

SPACE ENERGY CONVERSION R&T

OBJECTIVE

Provide the technology to meet power system requirements for future space missions, including growth Space Station, Earth orbiting spacecraft, lunar and planetary bases, and solar system exploration

SPACE ENERGY CONVERSION R&T

POWER TECHNOLOGY

R&T BASE ELEMENTS

- PHOTOVOLTAIC ENERGY CONVERSION
- CHEMICAL ENERGY CONVERSION
- THERMAL ENERGY CONVERSION
- POWER MANAGEMENT
- THERMAL MANAGEMENT

"TECHNOLOGY PUSH"

FOCUSED TECHNOLOGY PROGRAMS

- SPACE NUCLEAR POWER
- HIGH CAPACITY POWER
- SURFACE POWER & THERMAL MANAGEMENT
- MOBILE SURFACE SYSTEMS (POWER)
- LASER POWER BEAMING
- EARTH ORBITING PLATFORMS POWER & THERMAL MANAGEMENT
- SPACECRAFT POWER & THERMAL MANAGEMENT

"MISSION PULL"

BASE R&T PROGRAM

SPACE ENERGY CONVERSION R&T

OBJECTIVES

- **Programmatic**

  Provide the technology base to meet power system requirements for future space missions, including growth Space Station, Earth orbiting spacecraft, lunar and planetary bases, and solar system exploration

- **Technical**

  ≥300 W/kg Planar Array Technology
  100 - 200 Wh/kg Batteries
  ≥20% System Efficiency (Thermal-to Electric)
  >0.6 W/cm3 and >20 W/kg PMAD
  1 - 4 kg/m2 Radiator Specific Mass

SCHEDULE

- 1992 12-panel APSA
  Complete critical technology experiments for liquid sheet radiator (LSR)
- 1993 5-Ah Li-TiS2 Engineering Model Demo
  Solar Dynamic Heat Receiver Tech Demo
  Prototype Smart Pole (PMAD)
- 1994 Demonstrate thin 20% InP Cell
  Deliver Bipolar Flight Battery
  15% Efficient, 3000-Hour AMTEC
- 1995 Complete 100 Wh/kg Nickel Hydrogen Battery
- 1996 Demo 600 K PMAD Test Bed
- 1997 Complete integrated thermal and electrical test of power electronics orbital replacement unit
- 1998 Demonstrate 2nd generation APSA (>200 W/kg)
- 1999 Ground test 330 W/m2, 1 kW Concentrator Array

RESOURCES ($M)

	CURRENT	"3X"	STRATEGIC
FY91	12.5	12.5	12.5
FY92	12.8	12.8	12.8
FY93	13.3	15.8	17.7
FY94	13.8	20.1	21.5
FY95	14.6	23.4	25.8
FY96	15.3	25.6	29.7
FY97	16.0	28.6	33.9

PARTICIPANTS

- **Lewis Research Center**
  Responsibility includes advanced solar cells, nickel hydrogen & sodium sulfur batteries; dynamic conversion systems; fault-tolerant/high-temperature PMAD; thermal management
- **Jet Propulsion Laboratory**
  Responsibility includes advanced arrays, lithium & advanced batteries; AMTEC; advanced thermoelectrics; power integrated circuits
- **Langley Research Center**
  Space-based laser power technology
- **Goddard Space Flight Center**
  Thermal management for space experiments

FOCUSED TECHNOLOGY PROGRAM

SPACE ENERGY CONVERSION R&T

OBJECTIVES

- **Programmatic**

  Provide the focused technology to meet power system requirements for lunar and planetary bases, planetary rovers, penetrators, Earth-orbiting spacecraft, and deep-space missions

- **Technical**

  ≥100 kWe space nuclear reactor (7 years full power)
  1300 K Stirling (35% eff) and Thermoelectric (Z=1.0)
  1000 W-h/kg RFC with 20,000 h operational life
  PV (30% eff) and Thermoelectric (14% eff) for rovers
  >300 W/kg PV array (rad hard/LILT resistant)

SCHEDULE

- 1993 Thermoelectric Multicouple, Z = .85
  Stirling, 1050 K, 25 kWe/cylinder, 25% efficient
- 1994 SP-100 NAT fuel pins fabricated/stored
  600 K radiator demonstration
- 1995 Restart SP-100 Nuclear Assembly Test (NAT) Site
  Mfg specs for Z = 1.0 Thermoelectric
  Complete Phase 1 Development (Laser Beaming)
- 1996 Complete SP-100 T/E Converter /TEM pump tests
  Stirling, 1050 K, 25 kWe/cylinder (35% eff.)
  Demonstrate 300 W/kg planar/100 W/kg InP conc.
- 1997 Ground demo of 2-kW solar dynamic system
  Complete 5000 h on fuel cell stack
  Complete Phase II Development (Laser Beaming)
- 1999 Stirling, 1300 K, 25 kWe/cylinder (35% eff.)
- 2001 Complete SP-100 flight-like IAT (lunar outpost)

RESOURCES ($M)

	Current	3X	Strategic
FY-91	24	24	24
FY-92	30.6	30.6	30.6
FY-93	29.5	55.6	61.7
FY-94	29.6	100.5	127.1
FY-95	24.8	131.1	172.7
FY-96	25	140.5	202.3
FY-97	26.1	161	151.5

PARTICIPANTS

- **Lewis Research Center**
  SP-100 space subsystems; lead for high capacity power, surface power; mobile systems power; power systems technology for platforms and rovers; FEL power beaming
- **Jet Propulsion Laboratory**
  Lead for SP-100 GES; power system technology for platforms and rovers; FEL power beaming
- **Langley Research Center**
  Laser power beaming
- **Goddard Space Flight Center**
  Thermal management
- **Johnson Space Center**
  Supporting technology for surface and mobile power
- **Marshall Space Flight Center**
  Support on FEL power beaming

SPACE ENERGY CONVERSION R&T

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Base R&T Work Breakdown Structure

- **PHOTOVOLTAIC ENERGY CONVERSION**
  - Advanced Cell Technology
  - Light-Weight Arrays
  - Advanced Blanket Technology
- **CHEMICAL ENERGY CONVERSION**
  - Primary and Secondary Batteries
  - Fuel Cells
  - Advanced Electrochemical Energy Storage
- **THERMAL ENERGY CONVERSION**
  - Advanced Solar Dynamic Power Technology
  - Advanced Thermoelectric Conversion
  - Alkali Metal Thermoelectric Conversion (AMTEC)
- **POWER MANAGEMENT**
  - Electrical Power Management Technology
  - Power Integrated Circuit Technology
  - Power Materials Technology
  - Space Environment Studies & Models
  - Laser Power Beaming
- **THERMAL MANAGEMENT**
  - Instrumentation/ Sensor Thermal Control
  - Advanced Radiator Concepts
  - Advanced Power Electronics Cooling

SPACE ENERGY CONVERSION R&T

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Focused Technology Work Breakdown Structure

- **SPACE NUCLEAR POWER**
  - Refractory Metal Reactor
  - Fuel Pins
  - High-Temperature Control System
  - TEM Pump
  - Thermoelectric Conversion
  - Heat-Pipe Heat-Rejection Systems
- **HIGH CAPACITY POWER**
  - Conversion Systems
    - Stirling
    - Thermo-electrics
  - Thermal Management
  - Power Management
  - Systems Diagnostics
  - Environmental Interactions
- **SURFACE POWER & THERMAL MANAGEMENT**
  - System Integration
  - Power Generation
  - Energy Storage
  - Electrical Power Management
  - Thermal Management
- **EARTH ORBIT PLATFORM POWER & THERMAL MANAGEMENT**
  - Planar & Concentrator Arrays
  - Solar Dynamic Module Ground Test
  - Long-Life, High-Energy-Density Batteries
  - High-Temperature PMAD
  - High-Capacity Heat Rejection
- **SPACECRAFT POWER & THERMAL MANAGEMENT**
  - Very Light-Weight Solar Arrays
  - High-Energy Density Energy Storage
  - High-Efficiency Thermal to Electric Conversion
  - Fault-Tolerant, Reconfigurable PMAC
  - Cryogenic Thermal Bus
- **LASER POWER BEAMING**
  - Free Electron Laser Options
  - Optics/ Beam Expander Options
  - PV Array & Power Conditioning
  - Testbed/ Site Integration/ Operation
  - Advanced Concepts

SPACE ENERGY CONVERSION R&T

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Fc :used Technology Work Breakdown Structure
(Continued)

MOBILE SURFACE SYSTEMS (POWER)

- System Integration
- Photovoltaic Power Generation
- Energy Storage
- Power Management & Distribution
- Dynamic Isotope Power System (DIPS) Ancillary Technology
- Thermal-to-Electric Generators
- Tribology

SPACE ENERGY CONVERSION R&T

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ROLES & PARTICIPANTS

POWER TECHNOLOGY

R&T BASE ELEMENTS

Photovoltaic Energy Conversion
LeRC (advanced cells/blankets)
JPL (light-weight arrays)

Chemical Energy Conversion
LeRC (adv. batteries/fuel cells)
JPL (adv. batteries)

Thermal Energy Conversion
LeRC (adv. solar dynamic)
JPL (thermoelectrics/AMTEC)

Power Management
LeRC (PMAD/Materials/Environment)
JPL (PICs technology)
LeRC (power beaming)

Thermal Management
GSFC (sensor thermal control)
LeRC (adv. radiators/electronics cooling)

FOCUSED TECHNOLOGY PROGRAMS

Space nuclear power
JPL (project management)
LeRC (space subsystems)
DOE/SDIO/GE/LANL/HEDL/etc.

High capacity power
LeRC (project lead/Stirling)
JPL (thermoelectrics)

Surface power & thermal mgmt
LeRC (lead/PV/Storage/EPM/TM)
JPL (PV/Storage/TM) GSFC (TM)
JSC (Storage/TM) LANL (Storage)

Mobile Surface Systems
LeRC (le
JPL (P ev/Battery/TE/PMAD)
JSC (Fu- verif. tests)

Laser Pow Beaming
MSFC (FEL Test Site/Optics)
JPL (Optics/PV)
LeRC (PV)

Earth Orbit Platform Pwr & Thermal Mgmt
LeRC (PV/Batteries/ Hi-Temp TM/PMAD)
JPL (PV/Li batt/PMAD)
GSFC (Lo-Temp TM)

Spacecraft Power & Thermal Mgmt
JPL (PV/PICs Mission/TE/AMTEC)
LeRC (PMAC/DIPS/ PV/Hi-Temp Rad/ Reactor Analyses
GSFC (Lo-Temp TM)

- Heat Pipe Performance
- Solar Array Module Plasma Interaction Experiment (SAMPIE)
- Thermal Energy Storage
- Sodium-Sulfur Battery

Integrated Technology Plan Process

FY'93 ITP IMPLEMENTATION PLAN

- **FOR NEAR-TERM NEEDS**

IN '93-'97 COMPLETE THE ONGOING PROGRAM; IMPLEMENT KEY SELECTED NEW TASKS	BY 1993 THRU 1997: DELIVER SELECTED HIGH-LEVERAGE SUBSYSTEM CAPABILITIES

- **FOR END-OF-DECADE NEEDS**

IN '93-'97 BEGIN HIGH PRIORITY R&T; BEGIN TO PUT CRITICAL R&T TESTBEDS & FACILITIES IN PLACE	BY 1998 THRU 2003: DELIVER MAJOR NEW SYSTEM CAPABILITIES; CONDUCT MAJOR DEMONSTRATIONS/FLIGHT EXPERIMENTS; BEGIN SIGNIFICANT USE OF SSF FOR R&T; LEVERAGE NASP DEMONSTRATIONS

- **FOR LONG-TERM NEEDS**

IN '93-'97 BEGIN SELECTED, LONG-TERM R&T EFFORTS	BY 2004 THRU 2011: DELIVER MAJOR NEW SYSTEM CAPABILITIES; BEGIN USE OF LUNAR OUTPOST FOR R&T; ACHIEVE MARS TECHNOLOGY READINESS

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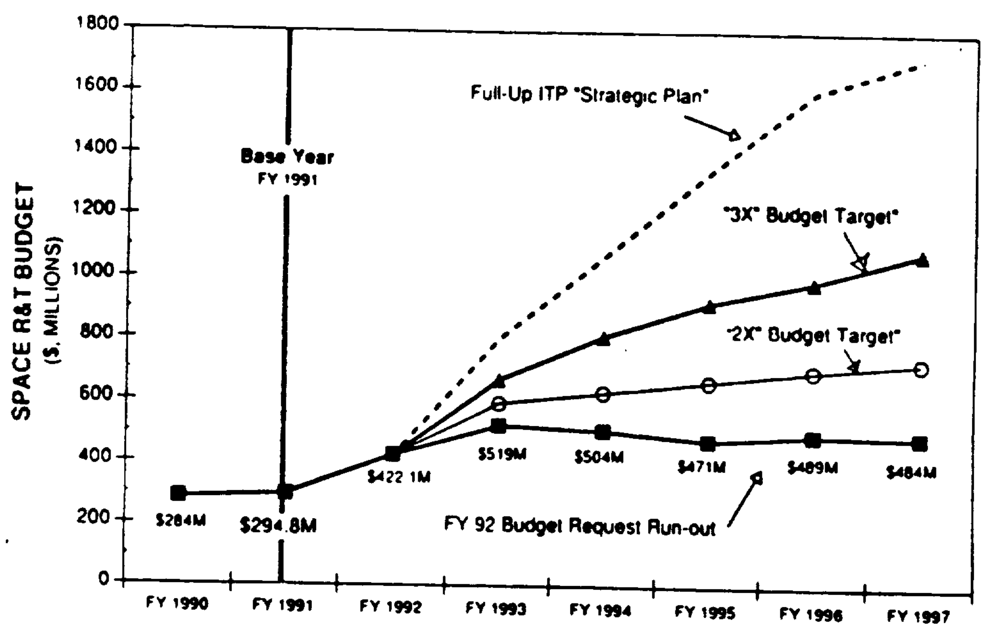
(JCM 7682a)

INTEGRATED TECHNOLOGY PL. FOR THE CIVIL SPACE PROGRAM

SPACE R&T BUDGET IMPLICATIONS



FLIGHT PROGRAMS FORECAST

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- **5-YEAR FORECAST INCLUDES**

'93 THRU '97: LIMITED NEW STARTS
- COMPLETION OF INITIAL SSF
- SOME SHUTTLE IMPROVEMENTS
- INITIAL EOS & EOSDIS
- SELECTED SPACE SCIENCE STARTS
- NLS DEVELOPMENT
- INITIAL SEI ARCHITECTURE SELECTION
- EVOLVING GEO COMMERCIAL COMMSATS
- MINOR UPGRADES OF COMMERCIAL ELVS

- **10-YEAR FORECAST INCLUDES**

'98 THRU '03: MULTIPLE NEW STARTS TO BE LAUNCHED IN 2003 THRU 2010
- SSF EVOLUTION/INFRASTRUCTURE
- FINAL SHUTTLE ENHANCEMENTS
- ADVANCED LEO EOS PLATFORMS/FULL EOSDIS
- MULTIPLE SPACE SCIENCE STARTS
- NLS OPERATIONS/EVOLUTION
- EVOLVING LAUNCH/OPERATIONS FACILITIES
- INITIAL SEI/LUNAR OUTPOST START
- DSN EVOLUTION (KA-BAND COMMUNICATIONS)
- NEW GEO COMMERCIAL COMMSATS
- NEW COMMERCIAL ELVS

- **20-YEAR FORECAST INCLUDES**

'04 THRU '11 MULTIPLE OPTIONS FOR NEW STARTS TO BE LAUNCHED IN 2009 THRU 2020
- SSF-MARS EVOLUTION
- BEGINNING OF AMLS/PLS DEVELOPMENT
- MULTIPLE SPACE SCIENCE STARTS
- DSN EVOLUTION (OPTICAL COMM)
- INITIAL MARS HLLV DEVELOPMENT
- EVOLVING LUNAR SYSTEMS
- MARS SEI ARCHITECTURE CHOSEN
- LARGE GEO COMMSATS
- NEW COMMERCIAL ELVS

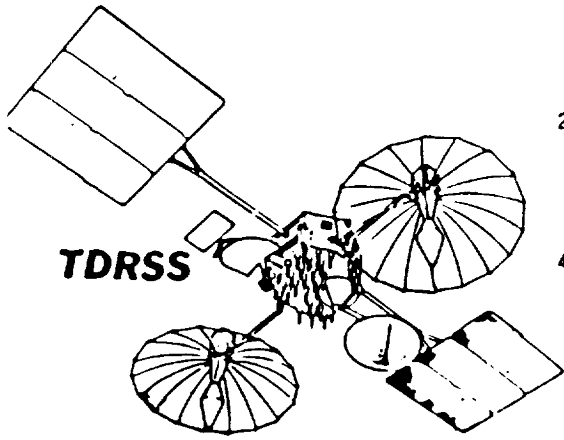
LBF40305a
(JCM 7602)

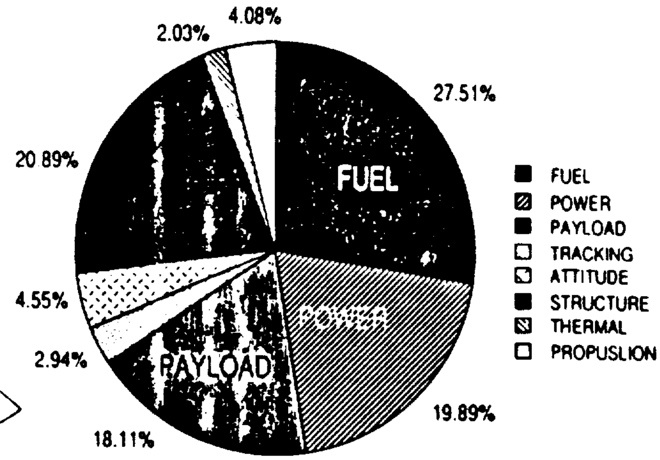
Space Power Background

NASA **ADVANCED TDRSS** OAET

PROPULSION POWER AND ENERGY

TRACKING AND DATA RELAY SATELLITE SYSTEM WET MASS





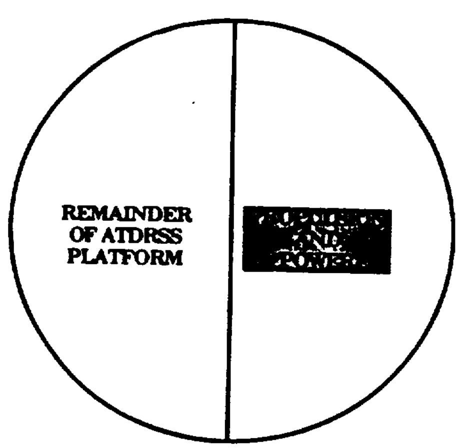
TOTAL MASS = 2123 kg

RK91 001 10

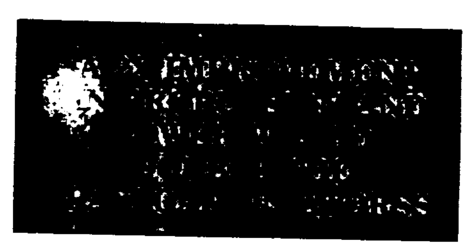
NASA **PROPULSION AND POWER DRIVERS ON ATDRSS** OAET

PROPULSION POWER AND ENERGY

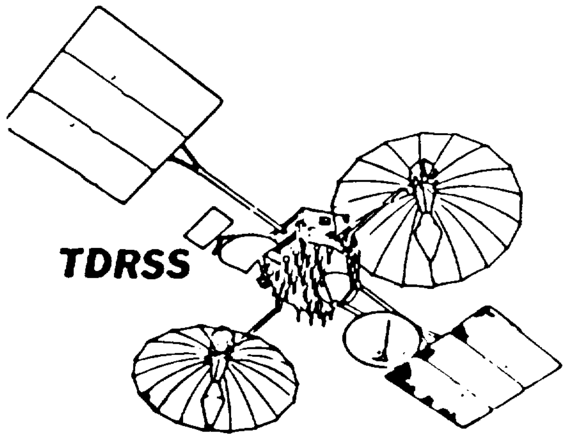
IMPROVEMENTS IN PROPULSION AND POWER CAN SIGNIFICANTLY IMPROVE ATDRSS

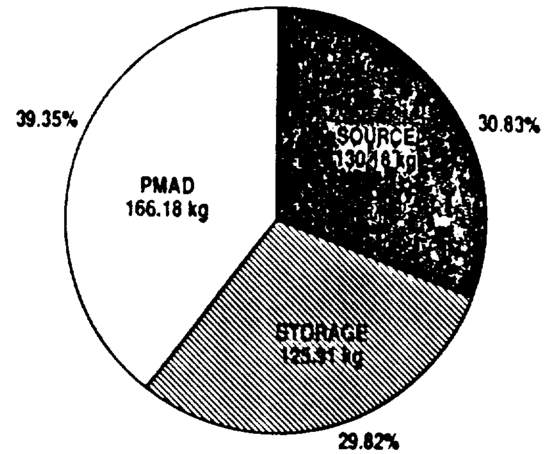


PROPULSION AND POWER COMPRISE ABOUT ONE-HALF OF THE TOTAL MASS OF ATDRSS



ELECTRICAL SUBSYSTEM MASSES





TOTAL EPS MASS = 422kg

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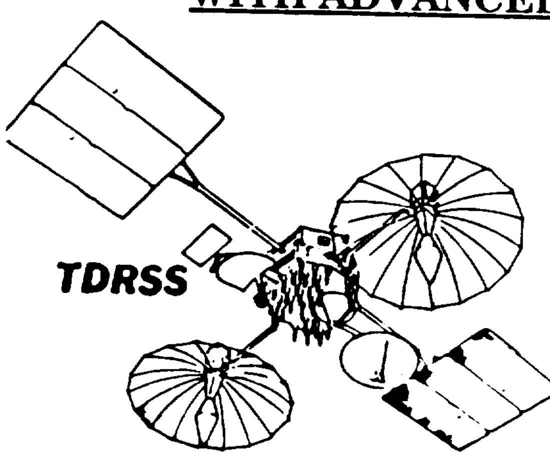
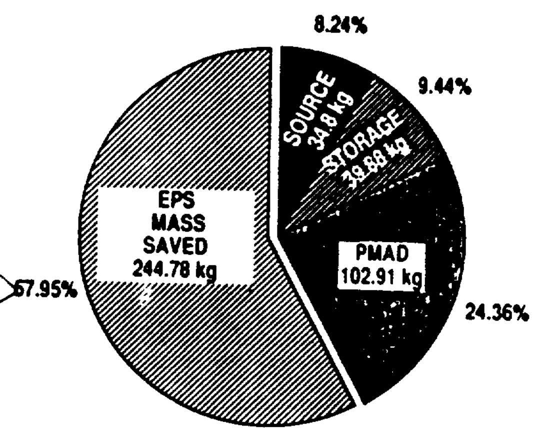
NASA ADVANCED TDRSS OAET
PROPULSION POWER AND ENERGY

ELECTRICAL POWER SYSTEM MASSES WITH ADVANCED TECHNOLOGIES





ADVANCED POWER SYSTEM TECHNOLOGIES CAN SAVE
245 kg IN THE ELECTRICAL POWER SYSTEM

BK91 001 17

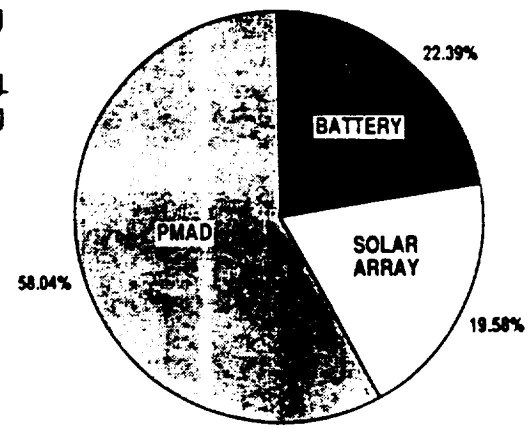
NASA ADVANCED TDRSS — OAET

PROPULSION POWER AND ENERGY

- NEW TECHNOLOGY ALLOWS 138% MORE POWER FOR THE SAME MASS
- FOR 422.3 kg, NEW TECHNOLOGY GIVES 5729 WATTS

SOLAR ARRAY MASS	82.67 kg
BATTERY MASS	94.53 kg
PMAD MASS	245.08 kg
	422.28 kg

- ADDITIONAL 3319 WATTS OF POWER AVAILABLE WITH NEW TECHNOLOGY FOR THE SAME MASS



5,729 WATTS
BOL POWER

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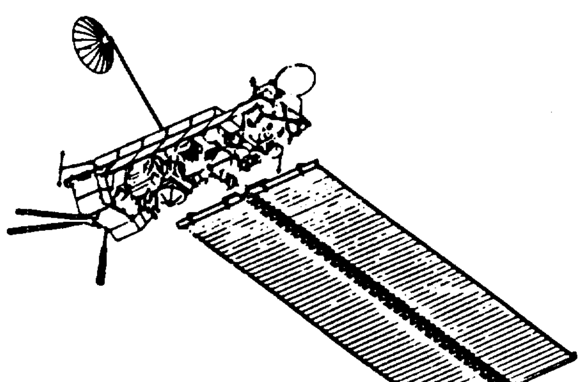
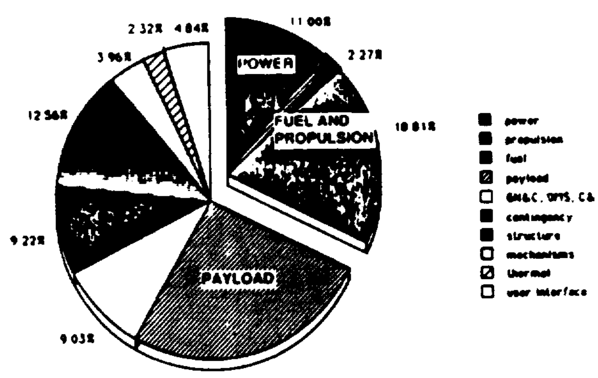
NASA Earth Observing System — OAST

POLAR ORBITING PLATFORM WET MASS

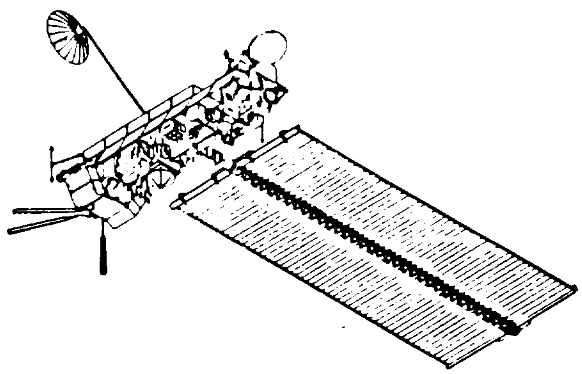


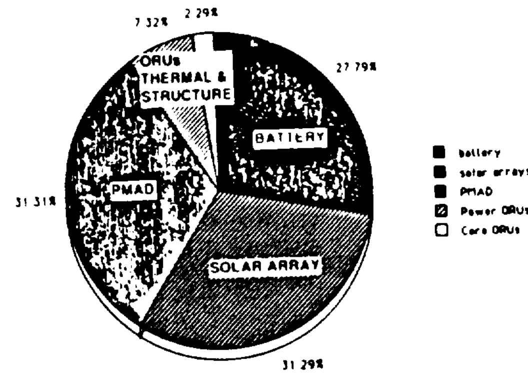


TOTAL WEIGHT IS 29715 lbs (13507 kg)

NASA Earth Observing System OAST

ELECTRICAL POWER SYSTEM WEIGHTS

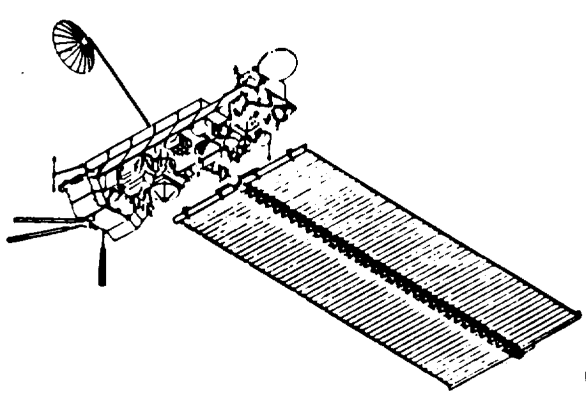


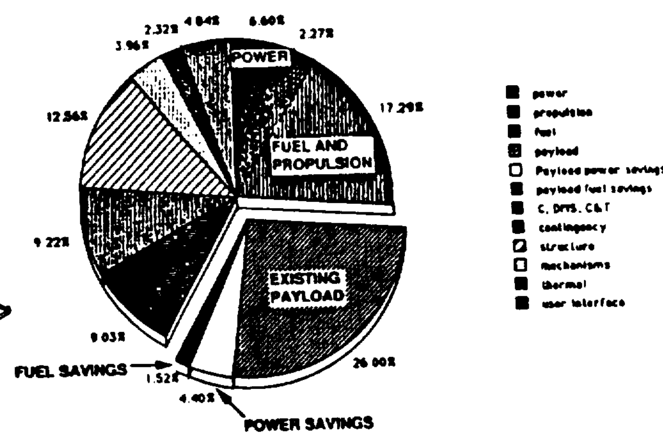


TOTAL EPS WEIGHT IS 3264.8 lbs (1484 kg)

NASA Earth Observing System OAST

POLAR PLATFORM WEIGHT WITH ADVANCED TECHNOLOGIES

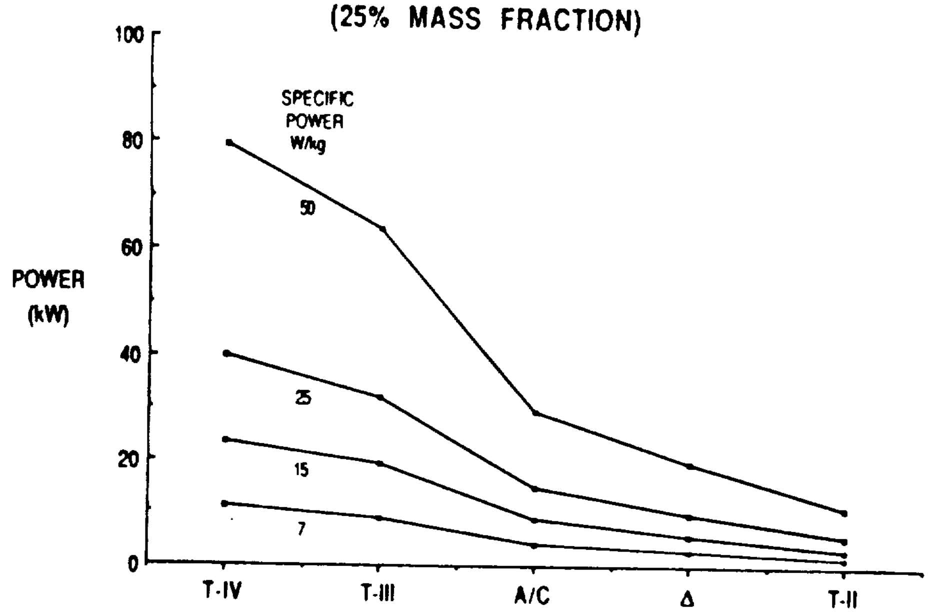




NEW TECHNOLOGIES ALLOW ~32% OF MASS TO BE PAYLOAD

IMPACT OF POWER SYSTEM SPECIFIC MASS ON GEO ORBIT POWER

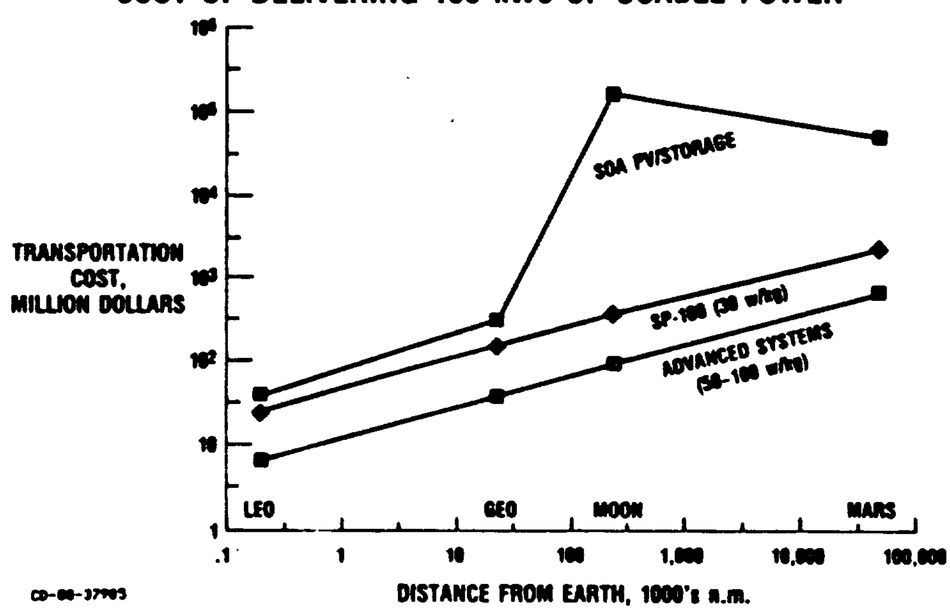
(25% MASS FRACTION)



KAF89.005.7

NASA
C-88-13153

COST OF DELIVERING 100 kWe OF USABLE POWER



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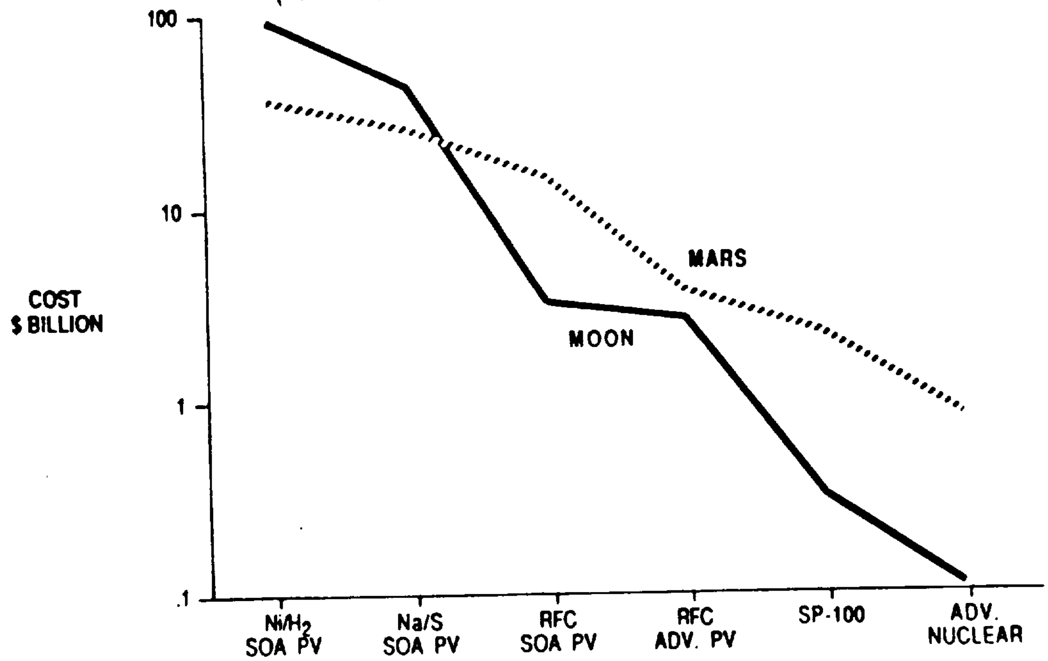
IMPACT OF POWER TECHNOLOGY ADVANCES ON TRANSPORTATION COSTS

(100 kWe, 1988 U.S. TRANSPORTATION COSTS)



SPACE ENERGY CONVERSION R&T

OAET

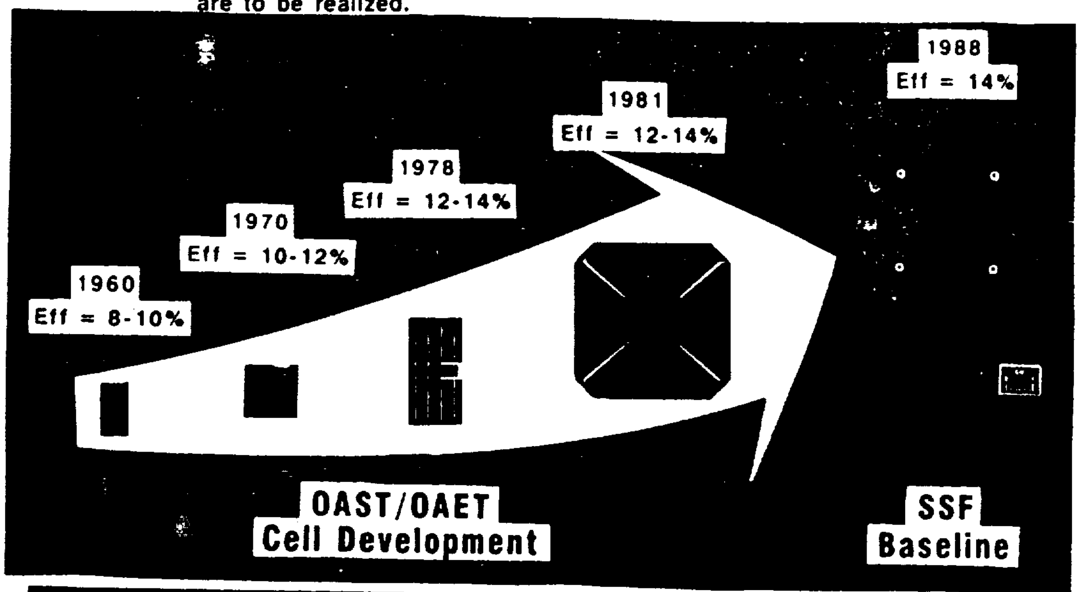
TECHNOLOGY SUPPORT

The Space Energy Conversion R&T Program Supports a Broad Range of Planned and Future NASA/DoD/Commercial Mission Power Requirements, Including

- Earth Observing Systems
- Space Station
- Communications Satellites
- Advanced Tracking and Data Relay Satellite System
- Lunar/Planetary Surface Power
- Planetary Spacecraft
- Electric Propulsion
- Missions to Comets and Asteroids
- Surface Explorers/Rovers
- Penetrators
- Launch and Orbital Transfer Vehicles

SPACE POWER TECHNOLOGY EVOLUTION

Space power technology evolution is and has been a long-term, steady improvement. There will be near-term spinoffs (as in the battery electrolyte for Hubble Space Telescope) as the technology evolves; however, there must be a long-term commitment to supporting the technology if the full benefits are to be realized.



EVOLUTION OF SILICON SPACE SOLAR CELL TECHNOLOGY

Technology Needs

SPACE ENERGY CONVERSION R&T

OAET

TECHNOLOGY NEEDS

- **OSSA**

  HIGHEST PRIORITY

  - 50 - 100 kWe Ion Propulsion (NEP) [Far-Term Need]

  SECOND HIGHEST PRIORITY

  - Solar Array/Cells [Near-Term Need]
  - Radiation Hardened Parts/Detectors [Near-Term Need]
  - Long-Life/High-Energy Density Batteries [Near-Term Need]

  THIRD HIGHEST PRIORITY

  - Mini RTG [Near-Term Need]
  - Thermal Control System [Mid-Term Need]

- **OSF**

  HIGHEST PRIORITY

  - Advanced Heat Rejection Devices (Heat Pumps/Heat Pipes)
  - High-Efficiency Space Power Systems (PV Concentrator Cells/Solar Dynamic Systems
  - Electromechanical Control Systems/Electrical Actuation (advanced, integrated electric power systems with surge/demand capability

SPACE ENERGY CONVERSION R&T

OAET

TECHNOLOGY NEEDS
(Continued)

- **MFPE/SEI**

  HIGHEST PRIORITY

  - Surface Power (Category 2)
  - Electric Propulsion (Category 3)

Space Power Reviews and Studies

SPACE ENERGY CONVERSION R&T

OAET

Summary of the 1990 Annual Review by the Space Systems & Technology Advisory Committee Aerospace Research & Technology Subcommittee

ESSENTIAL

- **Maintain Vigorous Base R&T Program**
  - Source of New Ideas and Techniques
  - Training Ground for Next Generation Space Technologists
  - Impacts "World Technology Position"
  - High Probability for Commercial Spin-Off
  - Archival Value
- **Develop Long-Range Defendable Strategies**
  - Cooperative Programs Wherever Possible
  - Emphasize Commercial Potential Where Obvious
- **Promote/Force User Acceptance**
  - Space Qualification
  - Tech Transfer Mechanism

SPACE ENERGY CONVERSION R&T

OAET

Summary of the 1990 Annual Review by the Space Systems & Technology Advisory Committee Aerospace Research & Technology Subcommittee

HIGH PRIORITY

- Space Nuclear Power
  - Long Lead Time Technology
  - SEI Essential
  - Cooperative Agreements
- Light Weight, Efficient Photovoltiacs
  - Growth Space Station
  - First Stages SEI
  - Commercial Spin Off
- Efficient Energy Dense Storage Technology
  - Regenerative Fuel Cells
  - Batteries
  - Thermal Storage
  - Significant Commercial Potential

SPACE ENERGY CONVERSION R&T

OAET

Summary of the 1990 Annual Review by the Space Systems & Technology Advisory Committee Aerospace Research & Technology Subcommittee

HIGH PRIORITY
(Continued)

- Efficient Energy/Power Dense Power Management and Conditioning
  - Major Contributions to Spacecraft Weight and Volume
  - Significant Commercial Potential
  - Major Uncertainty in Scale Up

SPACE ENERGY CONVERSION R&T

OAET

Summary of the 1990 Annual Review by the Space Systems & Technology Advisory Committee Aerospace Research & Technology Subcommittee

LOWER PRIORITY

- Power Beaming
  - No Strong Panel Advocate
  - Comments Ranged From Terminate to Keep Alive
- Solar Dynamic Power
  - User Should Develop (Space Station)
- AMTEC (Alkali Metal Thermoelectric Conversion)
  - Severe Materials Problem
  - Advanced Thermoelectrics/Thermionics Are Competitive
  - No Strong Panel Advocate

SPACE ENERGY CONVERSION R&T

OAET

Report of the Committee on Advanced Space Technology Aeronautics and Space Engineering Board National Research Council (1987)

SUMMARY RECOMMENDATIONS ON SPACE POWER

Space Power Supplies of the Future Should Include Photovoltaic, Solar Dynamic, and Nuclear Sources. Only Reactor-Generated Power Can Meet Anticipated High-Power Requirements, and NASA should Increase Its Involvement in the SP-100 Program, an Interagency Nuclear Space Power (SP) Research and Demonstration Program Designed to Achieve 100 kW of Space-Based Power.

SPACE ENERGY CONVERSION R&T

OAET

Report of the Committee on Advanced Space Technology
Aeronautics and Space Engineering Board
National Research Council
(1987)

SPECIFIC RECOMMENDATIONS ON SPACE POWER

It is Recommended that NASA Continue to Strengthen Its Solar Power Technology and Stirling Engine Development Programs. It Should Build an Integrated Approach to Improving the Spacecraft Bus for a Wide Range of Mission Needs. This Also Should Include Meeting Lunar and Planetary Rover Requirements. NASA Should Expand the Scope and Magnitude of Its Nuclear Power Development Program. Specifically, NASA Should Become a Stronger Resource Contributor to the Total SP-100 Program, Expanding Its Effort, Now Limited to Conversion System Technologies. It Should, in Fact, Become a Full Partner in SP-100, Applying More of Its Resources to the Mainstream of the Program.

SPACE ENERGY CONVERSION R&T

OAET

Report of the Committee on Advanced Space Technology
Aeronautics and Space Engineering Board
National Research Council

SPECIFIC RECOMMENDATIONS ON SPACE POWER (Continued)

Further, NASA Should Review Its Most Stressing Missions by Defining Requirements and Evaluating Power System Options Against the Specific Requirements. Optimal Combinations of Power Sources Should be Defined and R&D Programs Initiated on a Time Frame Appropriate With Anticipated Mission Scenarios. For the Nuclear Reactor Power System Option in Particular, it is Important to Introduce it Neither Too Soon Nor Too Late in This Long-Term Scenario.

Much to be Preferred is an Orderly, Properly Paced, Goal-Oriented R&D Program. This Program Should be Coordinated and Made Complementary to all of the Existing Programs and Sponsors . . . In Short, a National Space Nuclear Power Program is Needed . . .

SPACE ENERGY CONVERSION R&T

OAET

Report of the Committee on Advanced Space Technology
Aeronautics and Space Engineering Board
National Research Council
(1987)

CONCLUSIONS AND OBSERVATIONS ON SPACE POWER

As Energy Requirements for Scientific, Military, and Commercial Missions Increase, There Will be a Need for Larger, More Utility-Like Energy Systems. Desirable Power Supplies Include Photovoltaic, Solar Dynamic, and Nuclear; However, Only Nuclear Reactor Generated Power Can Meet Very High Requirements. The Space Nuclear Power Program has a Start-Stop History. It is Recommended that NASA Increase Its Participation in the SP-100 Program to Ensure That Its Own Future Requirements for High Energy are Met. R&D on Photovoltaic, Solar Dynamic, Stirling Engine, and Other Power Conversion Development Should Continue.

SPACE ENERGY CONVERSION R&T

OAET

Report of the 90-Day Study on Human Exploration of the Moon and Mars
1989

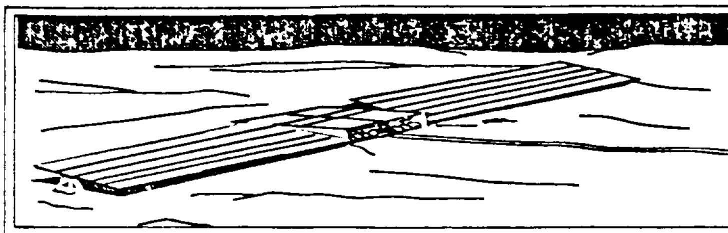
OTHER TECHNOLOGY NEEDS

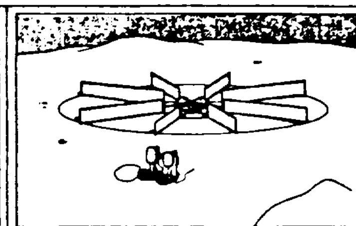
- IN-SPACE OPERATIONS
- EARTH-TO-ORBIT TRANSPORTATION
- SPACE TRANSPORTATION
- SURFACE SYSTEMS
  (includes surface nuclear power and surface solar power with chemical energy storage)
- HUMANS IN SPACE
- LUNAR AND MARS SCIENCE
- INFORMATION SYSTEMS AND AUTOMATION

NASA *Exploration Initiative*

Lunar Surface Power System Options

Strategy: Early Outpost Power Needs → Later Outpost Power Needs



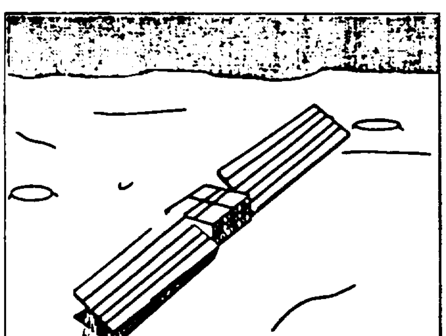


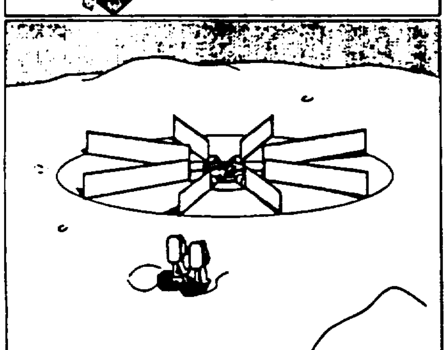
- Power Generation
  - Photovoltaic Arrays or Solar Dynamic Modules
    - Low-Moderate Mass/kW
    - Near Term Development
    - Can Be Located Near Outpost
    - Ease of Deployment
    - Daytime Power Only
    - Power Storage Required
    - Moderate Spares
    - Moderate Crew Support
- Power Storage
  - Batteries
    - Near Term Development
    - High Initial Mass/kW
    - Short Lived Systems
  - Regenerative Fuel Cells
    - Longer Term Development
    - Moderate Mass/kW
    - Short Lived Systems
    - High Spares/Resupply
- Nuclear Power
  - Continuous Day/Night Power
  - No Power Storage Required
  - Low Initial Mass/kW
  - Lowest Spares/Resupply
  - Long Life Systems
  - Minimum Crew Support
  - Longer Term Development
  - Must Be Remote to Outpost
  - Radiation Shielding
  - Political

Technical Study Group

NASA *Exploration Initiative*

SURFACE POWER SYSTEMS





PHOTOVOLTAIC ARRAY/ REGENERATIVE FUEL CELL

- Initial outpost power source
- 25/12.5 kW day/night capability
- State-of-the-art technology with large experience base
- Low power/mass ratio (1.5-3 W/kg)
- High resupply and sparing mass requirements (1t/year/unit)

SP-100 NUCLEAR REACTOR

- Dynamic engine power conversion
- 100 kW day/night capability
- High power/mass ratio (25-60 W/kg)
- Long life, high reliability system (7 year life)

Technical Study Group

SPACE ENERGY CONVERSION R&T

Report of the Committee on Human Exploration of Space
National Research Council
(1990)

NUCLEAR ELECTRIC POWER

The Committee Believes that Nuclear Power Eventually Will be Essential for Lunar and Mars Bases. . .

At Present, the Only Active Technology Program Applicable to this Need is the SP-100 Thermoelectric Space Reactor, Which has Been Pursued Under a Tri-Agency Program for Several Years. SP-100 Was Initiated in the Absence of a Definite Mission Requirement as a General Purpose Space Reactor Power Source. This Program Should be Redefined in Light of the Requirements of the HEI and Committed to Development; Nuclear Thermionic Research Should Continue to be Pursued as Well.

SPACE ENERGY CONVERSION R&T

Report of the Committee on Human Exploration of Space
National Research Council
(1990)

NUCLEAR ELECTRIC POWER
(Continued)

Consideration Should be Given to Demonstration of the Nuclear Electric Power System as the Power Source for an Electric Propulsion System, Which May Have Application to Science Missions With Large Launch Velocity Requirements. (In Fact, a Number of Outer Planet Missions Have Been Suggested, Including a Jovian System Grand Tour, That Will Require Such Advanced Power Sources.) Here, as With the Nuclear Rocket, Considerations of Safety Must Be Incorporated into Research, Development, and Demonstrations and Factored into Assessments of Overall System Performance. The Nuclear Electric System Might be Demonstrated Within These Constraints by a Mission in Which the System is Launched to a High Orbit, Say 600 Miles, Before It is Operated. The Orbit Could Then be Raised by Nuclear-Electric Propulsion to Geosynchronous Orbit or Beyond.

Report of the Advisory Committee On the Future of the U. S. Space Program

Principal Recommendations Concerning Space Goals

- A science program, which enjoys highest priority within the the civil space program, and is maintained at or above the current fraction of the NASA budget
- A Mission to Planet Earth (MTPE) focusing on environmental measurements
- A Mission from Planet Earth (MFPE), with the long-term goal of human exploration of Mars, preceded by a modified Space Station which emphasizes life sciences, an exploration base on the Moon, and robotic precursors to Mars
- A significantly expanded technology development activity, closely coupled to space mission objectives, with particular attention devoted to engines
- A robust space transportation system

NASA

NATIONAL SPACE POLICY – GOALS

On November 2, 1989, the President approved a national space policy that updates and reaffirms U.S. goals and activities in space.

- Strengthen the security of the United States
- Obtain scientific, technological, and economic benefits
- Encourage private sector investment
- Promote international cooperative activities
- Maintain freedom of space for all activities
- Expand human presence and activity beyond Earth orbit into the solar system

Office of Aeronautics, Exploration and Technology

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SPACE ENERGY CONVERSION R&T

OAET

REPORT OF THE SYNTHESIS GROUP RECOMMENDATIONS

SPECIFIC RECOMMENDATIONS ARE PROVIDED FOR THE EFFECTIVE IMPLEMENTATION OF THE SPACE EXPLORATION INITIATIVE

RECOMMENDATION 7

INITIATE A SPACE NUCLEAR POWER TECHNOLOGY DEVELOPMENT PROGRAM BASED ON THE SPACE EXPLORATION INITIATIVE REQUIREMENTS

The Program Must Concentrate on Safe, Reliable Systems to a Megawatt or Greater Level. These Nuclear Power Systems Will Be Required for Use on the Moon Before Use on the Mars Mission.

OAET

REPORT OF THE SYNTHESIS GROUP

POWER REQUIREMENTS

- TRANSPORTATION TO THE MOON REQUIRES POWER FOR ABOUT SEVEN DAYS FOR THE ROUND TRIP PLUS TIME IN LUNAR ORBIT
- TRANSPORTATION TO MARS INVOLVES TRIP TIMES ON THE ORDER OF A YEAR PLUS ORBITAL AND SURFACE OPERATIONS OF UP TO TWO YEARS
- SPACECRAFT WILL BE CONTINUOUSLY ROTATED IN CASES WHERE SOLAR FLUX IS VERY HIGH
- HABITAT POWER MUST HAVE A RELIABILITY >99.5%
- BASE POWER RELIABILITY CAN BE ABOUT 95%
- POWER UNITS SHOULD BE MADE OPERATIONAL
  - With a Minimum of Support Activities
  - Have Lifetimes Compatible with the Base
  - Be Serviceable
  - (If Nuclear) Be Refuelable and Disposable
- EVOLUTIONARY SYSTEMS DESIGNS ARE PREFERABLE TO SPECIFIC POINT DESIGNS WITHOUT GROWTH POTENTIAL

SPACE ENERGY CONVERSION R&T

OAET

REPORT OF THE SYNTHESIS GROUP

FUNCTIONAL ELECTRICAL POWER REQUIREMENTS

Functions	Mars Power	Moon Power	Suggested Technology
Transportation			
Spacecraft			
Piloted	to 20 kw	to 30 kw	Fuel cells (Moon) Nuclear/photovoltaics (Mars)(1)
Cargo	5 kw	5 kw	Fuel cells (Moon) Photovoltaics (Mars)
Lander	20 kw	20 kw	Fuel cells (w/wo photovoltaics)
Electric propulsion	to 5 Mw	to 5 Mw	Nuclear
Surface Activities			
Day only	20 kw		Photovoltaics
Habitat/lab			
Initial Operational Capability	to 30 kw	to 50 kw	Photovoltaics or nuclear (1)
Next Operational Capability	50 kw	100 kw	Nuclear
Base Power			
Initial Operational Capability	to 100 kw	to 100 kw	Nuclear
Next Operational Capability	to 800 kw	to 1 Mw	Nuclear
Rovers			
Unloader/Construction	240 kw-hr	240 kw-hr	Fuel cells
Pressurized			
Initial Operational Capability (per trip)	1900 hw-hr	1900 kw-hr	Fuel cells (2)
Next Operational Capability (per trip)	4800 kw-hr	4800 kw-hr	Fuel cells (2)
Unpressurized	100 kw-hr	100 kw-hr	Fuel cells (2)

(1) Depends on final power level
(2) In situ methane and oxygen produced on Mars may substitute for fuel cells.

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SPACE ENERGY CONVERSION R&T

OAET

REPORT OF THE SYNTHESIS GROUP
SUPPORTING TECHNOLOGIES

- HEAVY LIFT LAUNCH WITH A MINIMUM CAPABILITY OF 150 METRIC TONNES WITH DESIGNED GROWTH TO 250 METRIC TONNES
- NUCLEAR THERMAL PROPULSION
- NUCLEAR ELECTRIC SURFACE POWER TO MEGAWATT LEVELS
- EXTRAVEHICULAR ACTIVITY SUIT
- CRYOGENIC TRANSFER AND LONG TERM STORAGE
- AUTOMATED RENDEZVOUS AND DOCKING OF LARGE MASSES
- ZERO GRAVITY COUNTERMEASURES
- RADIATION EFFECTS AND SHIELDING
- TELEROBOTICS
- CLOSED LOOP LIFE SUPPORT SYSTEMS
- HUMAN FACTORS FOR LONG DURATION SPACE MISSIONS
- LIGHT-WEIGHT STRUCTURAL MATERIALS AND FABRICATION
- NUCLEAR ELECTRIC PROPULSION FOR FOLLOW-ON CARGO MISSIONS
- IN SITU RESOURCE EVALUATION AND PROCESSING

SPACE ENERGY CONVERSION R&T

OAET

REPORT OF THE SYNTHESIS GROUP
BASELINE DECISIONS FOR POWER

- FOR MARS, NUCLEAR POWER IS RECOMMENDED OVER PHOTOVOLTAICS DUE TO THE MASS SAVINGS. THE NUCLEAR UNITS WILL BE DEVELOPED TO MARS SPECIFICATIONS, AND THE MOON WILL BE USED TO VALIDATE THE DEPLOYMENT CONCEPT AND DEMONSTRATE SAFE AND RELIABLE OPERATION
  - Power Levels to a Megawatt for Base Power, Including Power for for in situ Resource Processing, Refueling Surface Vehicles, and Emergency Habitat Power
  - Designed for Both the Moon and Mars Environments
  - Specific Power >100 W/kg at 1 MW
  - Deployed With a Minimum of Robotic or Human Operations
  - Lifetimes Must Be on the Order of 30 Years
- ADVANCED REGENERATIVE FUEL CELLS COULD PROVIDE POWER FOR LUNAR SPACECRAFT, LANDERS, AND SURFACE VEHICLES, WITH PERFORMANCE GREATER THAN 1 kW-h/kg
- NUCLEAR POWER UNITS (10 TO 100 kW) CAN PROVIDE POWER FOR MARS SPACECRAFT AND LUNAR AND MARS SURFACE HABITATS. THESE SYSTEMS SHOULD HAVE A SPECIFIC POWER >15 W/kg AT 25 kW, RELIABILITY >99.5%, PASSIVE CONVERSION AND NO SINGLE FAILURE POINTS
- ADVANCED SOLAR PHOTOVOLTAIC ARRAYS, WITH SPECIFIC POWERS >200 W/kg, CAN PROVIDE POWER FOR SPACECRAFT AND DAYTIME SURFACE OPERATIONS

OAET

REPORT OF THE SYNTHESIS GROUP RECOMMENDATIONS FOR DEVELOPMENT PROGRAMS

- THE CURRENT SP-100 AND THERMIONIC PROGRAMS SHOULD BE RESTRUCTURED TO MEET SPACE EXPLORATION INITIATIVE REQUIREMENTS
  - All Technology Options Should be Considered
  - Technology Down-Selections Should be Based on Demonstrated Performance, Safety and Reliability
  - The Benefits Provided by Nuclear Power Systems are Extremely High and are Key Enablers for Many Initiative Activities; However, New Efforts to Develop Space Applications of Nuclear Power Should be Structured to Take Advantage of Lessons Learned From the SP-100 Program
- ADVANCED REGENERATIVE FUEL CELLS CAN BE DEVELOPED BY THE YEAR 2000. THE COST IS LOW WITH WIDE APPLICATION TO CRITICAL SURFACE SYSTEMS SUCH AS LANDERS AND ROVERS
- SOLAR PHOTOVOLTAIC ARRAYS COULD PLAY A WIDE RANGE OF ROLES IN THE INITIATIVE. INCREASING THE EFFICIENCY AND DECREASING THE WEIGHT OF SOLAR ARRAYS WILL CONTINUE TO PAY HIGH DIVIDENDS FOR BOTH SPACE- AND EARTH-BASED APPLICATIONS
- POWER BEAMING FOR SURFACE-TO-SURFACE POWER DISTRIBUTION MAY GREATLY REDUCE THE MASS OF ROVERS AND OTHER MOBILE SURFACE SYSTEMS, ASSUMING LINE OF SITE CONSTRAINTS CAN BE MET. IF NUCLEAR ELECTRIC PROPULSION IS DEVELOPED FOR USE IN THE LUNAR OR MARS CARGO VEHICLE, THE ORBITING TRANSFER VEHICLE MAY BE A CONVENIENT POWER SOURCE FOR SURFACE OPERATIONS (NOTED NEED TO CONSIDER COSTS)

Space Power Technology Development

SPACE ENERGY CONVERSION R&T

OAET

TECHNOLOGY DEVELOPMENT CHALLENGES/DRIVERS

- DEVELOP POWER SYSTEMS FOR AND EXTEND THEIR LIFE IN FUNCTIONAL ENVIRONMENTS (LEO, GEO, MOON, PLANETARY)
- INCREASE POWER DENSITY OF POWER SYSTEM
- REDUCE POWER SYSTEM MASS
- INCREASE POWER SYSTEM RELIABILITY
- ENABLE POWER SYSTEM OPERATION AT HIGHER TEMPERATURES

AUGMENTATION

- ACCELERATE DEVELOPMENT OF POWER SYSTEM TECHNOLOGIES
- AUGMENT R&T AREAS THAT ARE MINIMALLY FUNDED
- INITIATE MISSION-FOCUSED AND ADVANCED TECHNOLOGIES
- TRANSFER MATURING TECHNOLOGIES TO FOCUSED THRUSTS AND USERS

SPACE ENERGY CONVERSION R&T

OAET

TECHNOLOGY BENEFITS

- REDUCED LAUNCH WEIGHT
- INCREASED POWER FOR SAME MASS
- INCREASED LIFETIME
- INCREASED RELIABILITY
- REDUCED COSTS
- EXTENDED RANGE OF POWER SYSTEM CAPABILITIES
- REDUCED VOLUME

SPACE ENERGY CONVERSION R&T

OAET

TECHNOLOGY DEVELOPMENT APPROACH

- DEVELOP AND EVALUATE HIGH-EFFICIENCY, RADIATION-HARD SOLAR CELLS AND LIGHT-WEIGHT ARRAY SYSTEM COMPONENTS
- DEVELOP ADVANCED HIGH SPECIFIC ENERGY, HIGH ENERGY DENSITY, LONG CYCLE LIFE ENERGY STORAGE SYSTEMS
- DEVELOP IMPROVED THERMAL-TO-ELECTRIC CONVERSION SYSTEMS
  (Advanced thermoelectric materials, AMTEC, solar dynamic, Stirling)
- DEVELOP LIGHT-WEIGHT, SMART, HIGH-TEMPERATURE, COMPACT POWER MANAGEMENT AND CONTROL (PMAC)
- DEVELOP INNOVATIVE, LOW-MASS THERMAL TRANSPORT AND RADIATOR CONCEPTS
- DEVELOP SP-100 SPACE NUCLEAR REACTOR POWER SYSTEM

SPACE ENERGY CONVERSION R&T

OAET

TECHNOLOGY DEVELOPMENT APPROACH

(Continued)

- DEVELOP LASER POWER BEAMING CAPABILITY
- DEVELOP IMPROVED POWER SYSTEM MATERIALS
- DEVELOP ENVIRONMENTAL INTERACTIONS MODELS AND DESIGN GUIDELINES FOR FUTURE SPACE POWER SYSTEMS

SPACE ENERGY CONVERSION R&T

RECENT ACCOMPLISHMENTS

- SUCCESSFUL COMPLETION OF GROUND TESTING OF 130 W/kg ADVANCED PHOTOVOLTAIC SOLAR ARRAY (APSA)
- BOEING APPLICATION OF NASA-SPONSORED MINI-DOME FRESNEL LENS AND PRISMATIC CELL COVER TO ACHIEVE 31% AMO EFFICIENCY
- SUCCESSFUL COMPLETION OF 40,000 LEO CYCLES AT 80% DEPTH OF DISCHARGE (DOD) IN BOILER PLATE NICKEL-HYDROGEN CELLS
- SUCCESSFUL COMPLETION OF >10,000 CYCLES IN BIPOLAR NICKEL-HYDROGEN
- SUCCESSFUL ACHIEVEMENT OF 700 CYCLES AT 50% DOD IN 1-A-h LiTiS2 CELLS

SPACE ENERGY CONVERSION R&T

RECENT ACCOMPLISHMENTS
(Continued)

- SUCCESSFUL REPRODUCTION OF HI FIGURE-OF-MERIT SILICON-GERMANIUM-GALLIUM-PHOS DE N-TYPE MATERIAL
- DEMONSTRATED FEASIBILITY OF FABRICATION TECHNIQUES FOR SOLAR DYNAMIC CONCENTRATOR ALUMINUM PANELS
- DEMONSTRATED STABILITY OF LIQUID SHEET RADIATOR AT 1-G (VERIFIED ANALYTICAL PREDICTIONS)
- SUCCESSFULLY TESTED SILICON-CARBIDE MOSFET TO 500 C
- DEVELOPED MONTE CARLO MODEL FOR ATOMIC OXYGEN EROSION
- DEMONSTRATED 7X INCREASE IN ATOMIC OXYGEN DURABILITY WITH CVD-DEPOSITED SiO2 ON CARBON/CARBON COMPOSITE RADIATOR SURFACES

SPACE ENERGY CONVERSION R&T

SPACE POWER SYSTEMS

TECHNOLOGY NEEDS

HIGH POWER, HIGH EFFICIENCY,
LOW-MASS ELECTRICAL POWER SYSTEMS AND
THERMAL MANAGEMENT SYSTEMS FOR SPACECRAFT AND PLANETARY BASES

CURRENT PROGRAM S-O-A

COMMERCIAL SOLAR ARRAYS AT ~20 W/kg (RIGID) TO ~66 W/kg (FLEXIBLE); NASA/JPL LABORATORY DEMONSTRATION AT 130 W/kg; COMMERCIAL BATTERIES AT ~10 Wh/kg; NASA TECHNOLOGY >20 Wh/kg; THERMOELECTRIC EFFICIENCY <7%; AND POWER MANAGEMENT AND DISTRIBUTION (PMAD) AT <0.03 W/cm3 (AND <15 W/kg)

AUGMENTED PROGRAM

SOLAR ARRAYS AT 300 W/kg; BATTERIES AT 150 W-h/kg; STATIC THERMAL-TO-ELECTRIC CONVERSION ≥10%; PMAD AT ≥0.6 W/cm3 (AND 20 W/kg) TO ACHIEVE FACTOR OF TWO REDUCTIONS IN MASS OF ELECTRIC POWER SYSTEM ON SPACECRAFT

BASE RESEARCH AND TECHNOLOGY PROGRAM

SPACE ENERGY CONVERSION R&T

SUB-ELEMENT	STATE-OF-THE-ART	OBJECTIVE
PHOTOVOLTAICS	Comm: 20 W/kg (rigid) to 66 W/kg (flex.) Demo: 100 W/kg (rigid) to 130 W/kg (flex.) 240 W/m2	> 300 W/kg (flex.) 1000 W/kg (blanket) >300 W/m2 (concentrator)
CHEMICAL ENERGY CONVERSION	Comm: 10 Wh/kg Demo: >20 Wh/kg	150 Wh/kg (75 % DOD)
THERMAL ENERGY CONVERSION	< 7 % efficiency	> 10 % efficiency
POWER MANAGEMENT	< 0.03 W/cm3 <15 W/kg	> 0.6 W/cm3 > 20 W/kg
THERMAL MANAGEMENT	10 kg/m2	1-4 kg/m2

BASE RESEARCH AND TECHNOLOGY PROGRAM

SPACE ENERGY CONVERSION R&T

SPACE POWER SYSTEMS

MISSION SPECIFIC

300 W/m2 CONCENTRATORS, 300 W/kg SOLAR ARRAYS
100 W-hr/kg BATTERIES
600K POWER ELECTRONICS AND THERMAL CONTROL
HIGH FREQUENCY POWER
ATOMIC OXYGEN PROTECTIVE COATINGS/ARC PROOF SOLAR ARRAYS
ORBITAL AND PLANETARY SURFACE ENVIRONMENTAL DESIGN GUIDELINES

BREAKTHROUGH

Li/CO2 FUEL CELLS
BEAMED POWER SYSTEMS
LUNAR REGOLITH STORAGE
1-2 kg/m2 RADIATORS/ADVANCED HEAT PIPES
DIAMOND FILM POWER ELECTRONICS

CAPABILITY

PV PERFORMANCE VERIFICATION/FUNDAMENTALS
ELECTROCHEMICAL ADVANCED DIAGNOSTICS/MODELLING
SOLAR DYNAMIC DESIGN/ANALYSIS
HEAT PIPE CODE VALIDATION
SPACE ENVIRONMENTAL SIMULATION FACILITIES

RJS91-004.1

BASE RESEARCH AND TECHNOLOGY PROGRAM

SPACE ENERGY CONVERSION TECHNOLOGY

OAET

AUGMENTATION STRATEGY

- HIGH-RISK, INNOVATIVE POWER TECHNOLOGIES THAT HAVE THE POTENTIAL OF HIGH PAYOFF FOR FUTURE MISSIONS
  - DIAMOND FILM POWER ELECTRONICS
  - Li/CO_2 FUEL CELLS
- MAINTAIN A BALANCE BETWEEN TECHNOLOGY ELEMENTS TO SUPPORT EVOLUTIONARY SPACECRAFT POWER SYSTEM NEEDS
  - PHOTOVOLTAIC ENERGY CONVERSION
  - CHEMICAL/THERMAL ENERGY CONVERSION
  - POWER/THERMAL MANAGEMENT
- MAINTAIN SPECIFIC ACTIVITIES TO ENHANCE NASA'S CAPABILITY TO RESPOND TO TECHNOLOGY NEEDS
  - ADVANCED DIAGNOSTICS/MODELLING
  - SPACE ENVIRONMENTAL SIMULATION FACILITIES

OAET

AUGMENTATION STRATEGY

- DEVELOP HIGH-RISK, INNOVATIVE POWER TECHNOLOGIES THAT HAVE THE POTENTIAL OF HIGH PAYOFF FOR THE SPACE EXPLORATION INITIATIVE (SEI) AND OTHER SPACE MISSIONS.

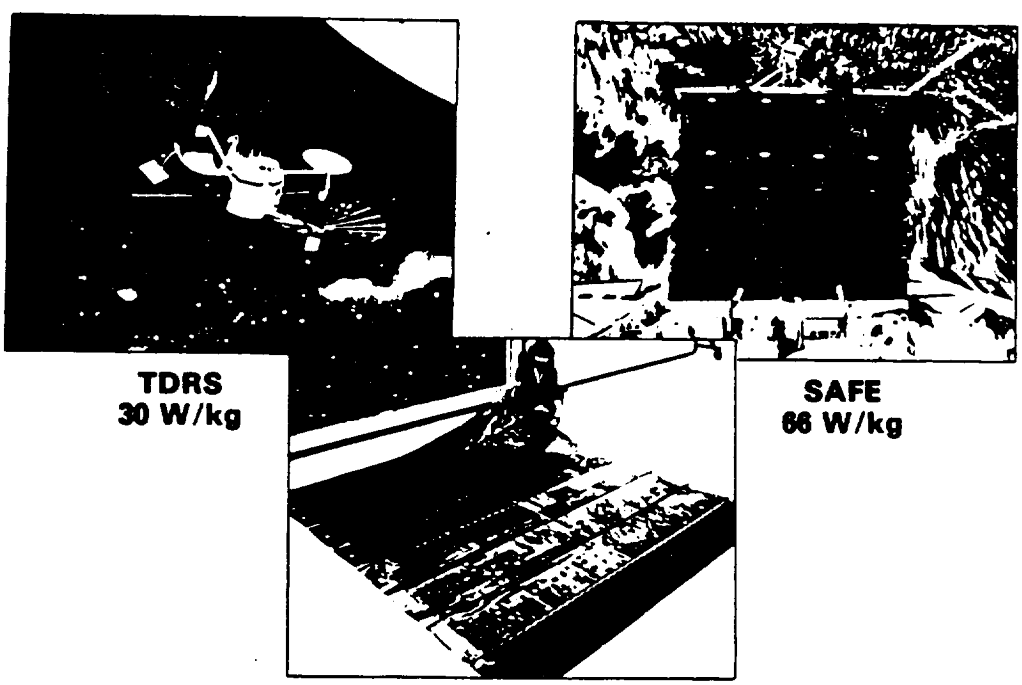
  EXAMPLES:
  - SP-100 coupled with advanced conversion and radiators
  - High specific energy regenerative fuel cells
  - Laser power beaming

- BUILD ON BASE R&T PROGRAM TO FOCUS ON FUTURE SPACECRAFT POWER NEEDS

  EXAMPLES:
  - Chemical/thermal energy conversion tie into high capacity power and surface power, etc.
  - Power/thermal management tie into focused power programs

→ "MISSION PULL" ←

PROGRESS IN SOLAR ARRAY TECHNOLOGY



TDRS
30 W/kg

SAFE
66 W/kg

APSA
130 W/kg

RP89-388 (3)

SPACE ENERGY CONVERSION R&T

OAET

PHOTOVOLTAIC ENERGY CONVERSION

- OBJECTIVES

  Provide the technology for photovoltaic arrays with improved conversion efficiency, reduced mass, reduced cost, and increased operating life for advanced space missions

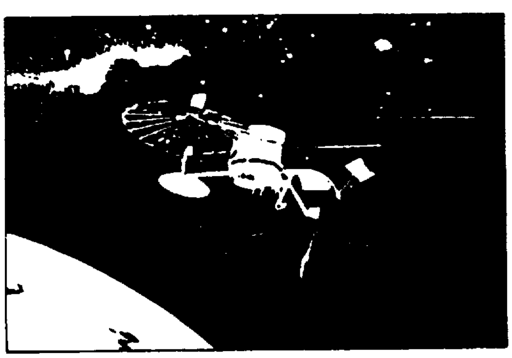
- PARTICIPANTS
  - Lewis Research Center
  - Jet Propulsion Laboratory
  - Industry/University Contracts

- AUGMENTATION
  - Accelerate work on Advanced Photovoltaic Solar Array
  - Development of thin 20% efficient InP solar cell (radiation hard)
  - Accelerate development of thin-film flexible blanket
  - Demonstrate high-temperature blanket
  - Ground test 330 W/m2 1-kWe concentrator array

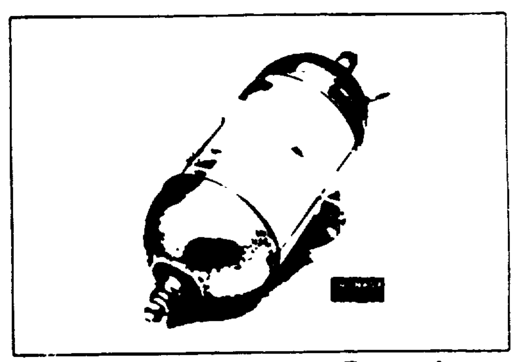
- PAYOFF

  Lighter weight, longer lived arrays

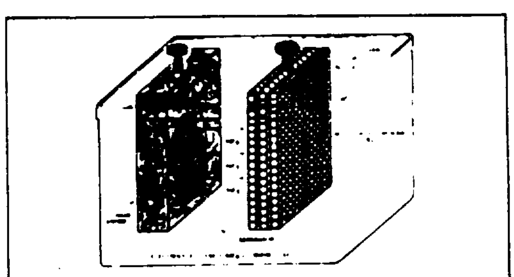
PROGRESS IN ENERGY STORAGE



TDRS
Nickel Cadmium - 10 W-hr/kg



Space Station and Beyond
Nickel Hydrogen - 20+ W-hr/kg



Future Applications
Lithium Titanium Disulfide - 40+ W-hr/kg

OAET

CHEMICAL ENERGY CONVERSION

- OBJECTIVES

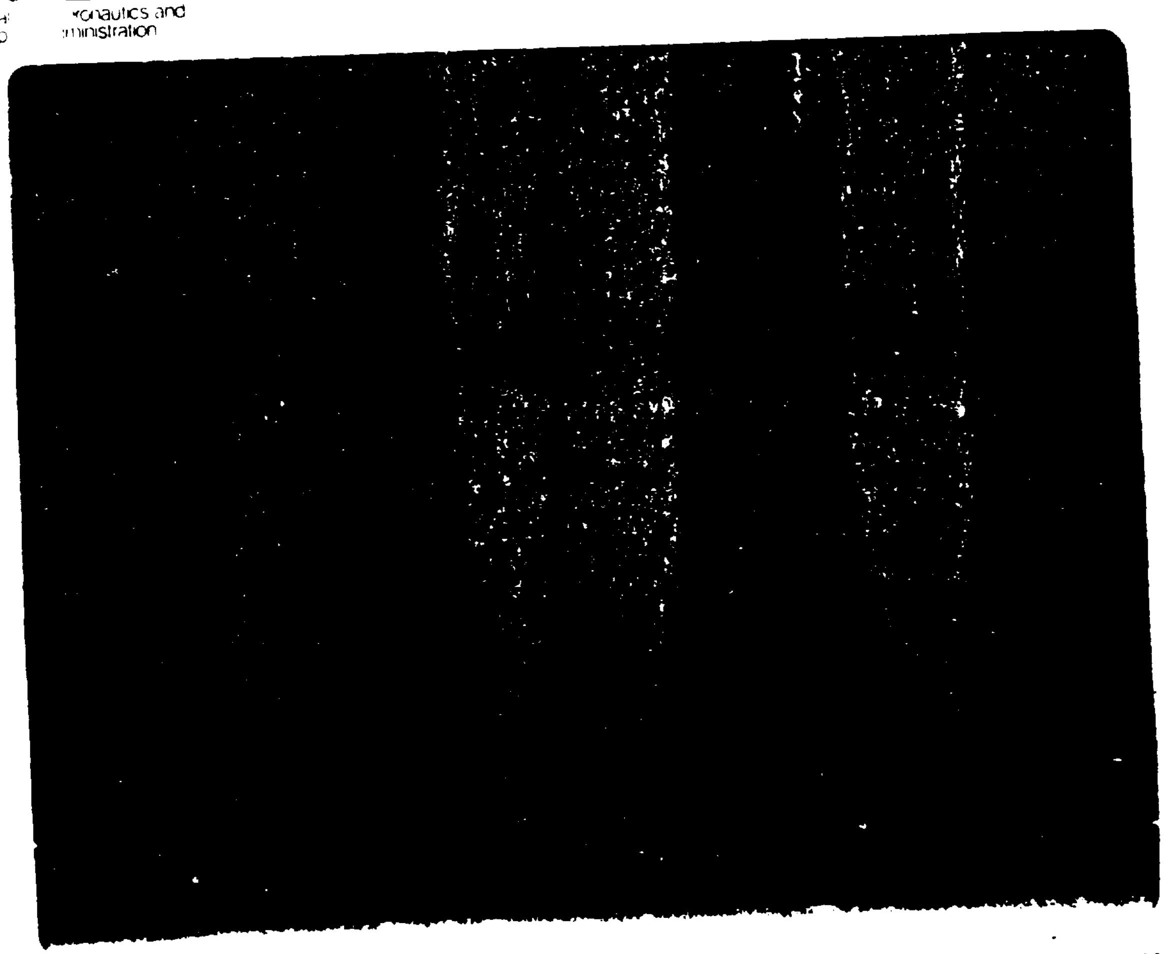
  Provide the technology base for advanced electrochemical energy conversion and storage systems required to support the low to high power needs and cycle life requirements for future space missions

- PARTICIPANTS
  - Lewis Research Center
  - Jet Propulsion Laboratory
  - Industry/University Contracts

- AUGMENTATION
  - Accelerate work on sodium sulfur batteries
  - Expand/enhance work of fuel cell catalysts
  - Develop and transfer lithium secondary battery technology
  - Accelerate development of 150 W-h/kg cell
  - Initiate electrochemical capacitor work

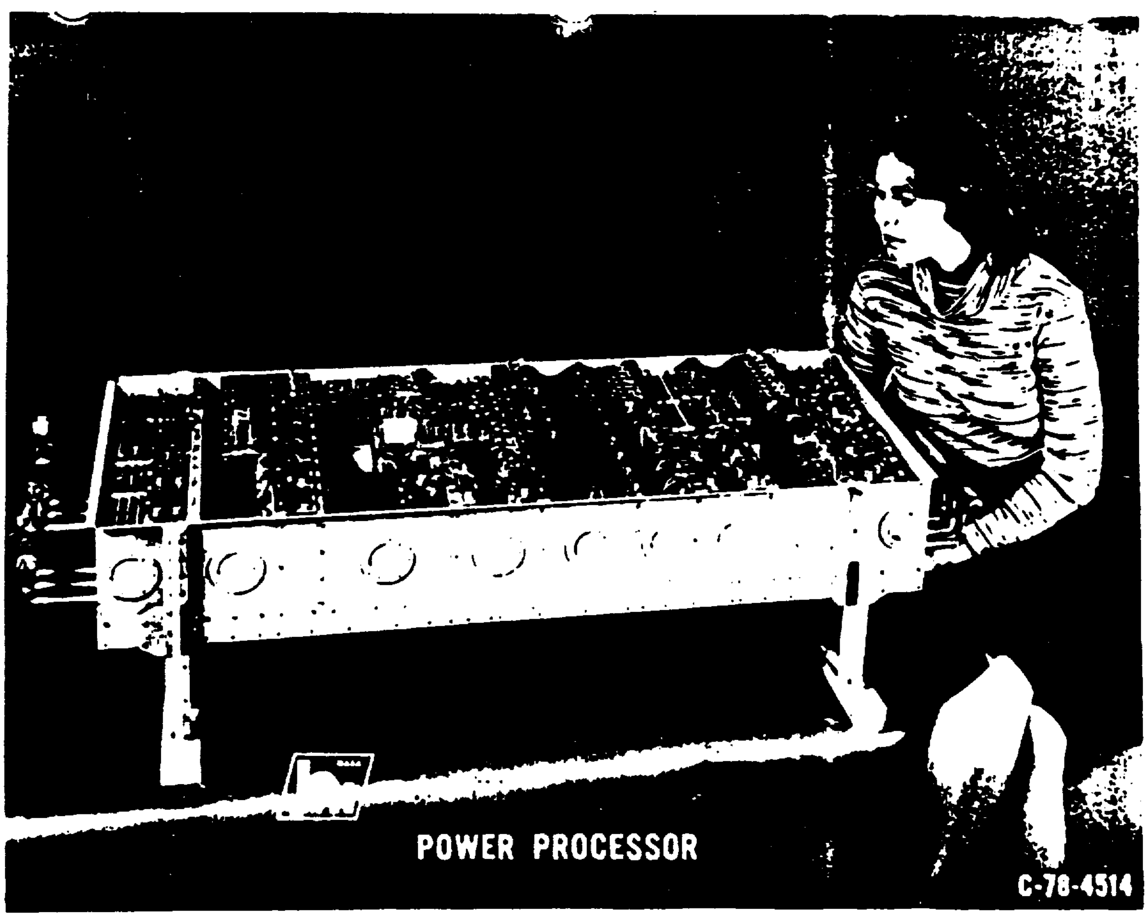
- PAYOFF

  Lighter weight, longer lived batteries/More power for same mass



THERMAL ENERGY CONVERSION

- OBJECTIVES
  - Develop the technology base to provide advanced high-efficiency, high-temperature, long-life solary dynamic Stirling/Brayton power system
  - Develop new thermoelectric material with significantly higher figure of merit
  - Investigate and demonstrate the feasibility of high-power, long-life alkali metal thermoelectric converter (AMTEC)
- PARTICIPANTS
  - Lewis Research Center
  - Jet Propulsion Laboratory
  - Industry/University Contracts
- AUGMENTATION
  - Accelerate development of static conversion technologies
  - Verify thermal energy storage technologies for lunar base application
- PAYOFF
  - Reduction is radioisotope inventory
  - Reduction in transported mass to Moon



SPACE ENERGY CONVERSION R&T

OAET

POWER MANAGEMENT

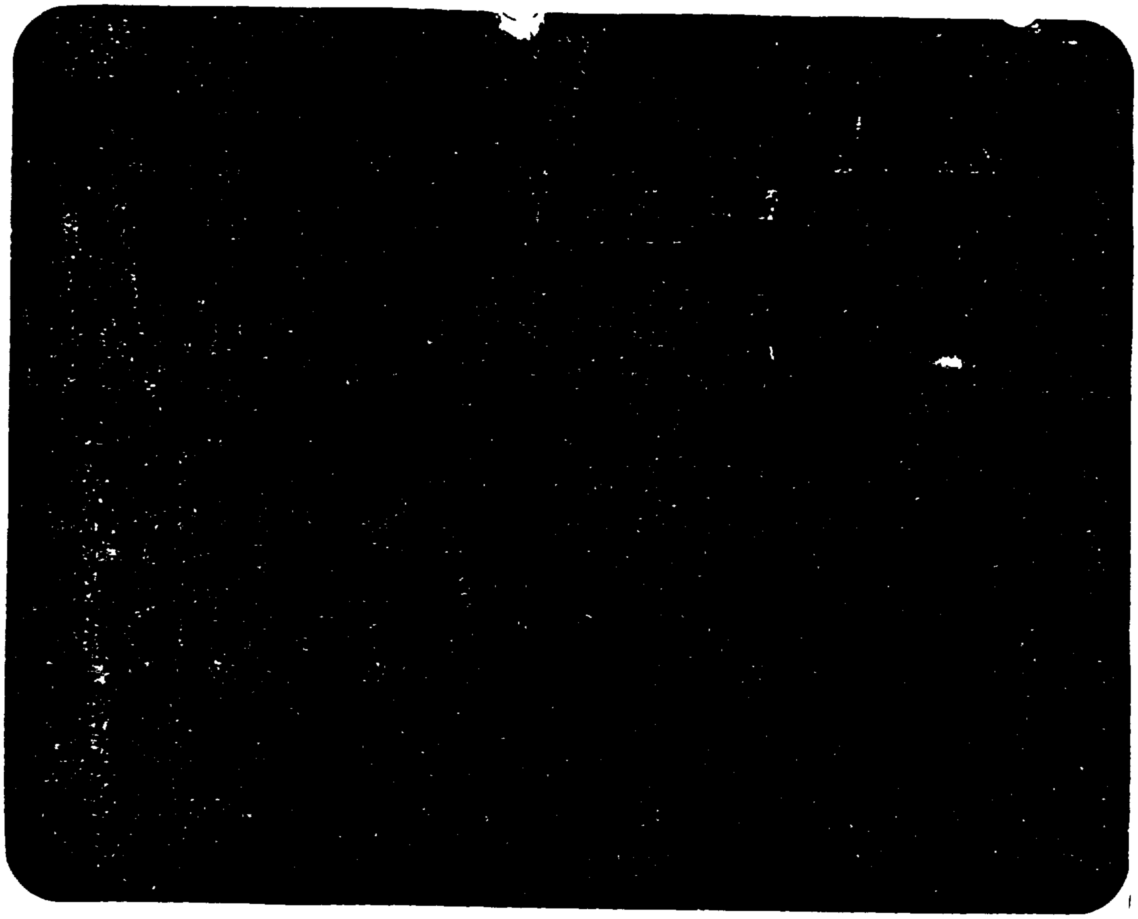
- OBJECTIVES
  - Develop the electrical power systems conditioning, control, and distribution technology for future space missions
  - Development of the capability to model power systems (including environmental interactions)
  - Development of advanced concepts (e.g., power beaming and advanced power management materials)
- PARTICIPANTS
  - Lewis Research Center
  - Jet Propulsion Laboratory
  - Langley Research Center
  - Industry/University Contracts
- AUGMENTATION
  - Brings Power Management up to its level of importance
  - Accelerates work on modular, high-temperature, smart PMAD
- PAYOFF
  - Reliable, fault-tolerant power systems
  - Reduced mass, reduced volume, reduced parts count

SPACE ENERGY CONVERSION R&T

OAET

THERMAL MANAGEMENT

- OBJECTIVES
  - Develop the technology base for versatile thermal management systems for next generation of space missions
  - Provide advanced thermal management technology for both high and moderate temperatures, including technology for thermal control of instrument systems
- PARTICIPANTS
  - Goddard Space Flight Center
  - Lewis Research Center
  - Industry/University Contracts
- AUGMENTATION
  - Brings Thermal Management up to its level of importance
  - Provides additional options for thermal management
- PAYOFF
  - Reduction in radiator size and mass
  - Major improvement ($\geq$50%) in sensor cooling



SPACE ENERGY CONVERSION R&T

SPACE NUCLEAR POWER

- OBJECTIVES

  Develop and validate the technologies for safe and reliable space nuclear reactor power systems to support lunar and Mars exploration missions

- PARTICIPANTS

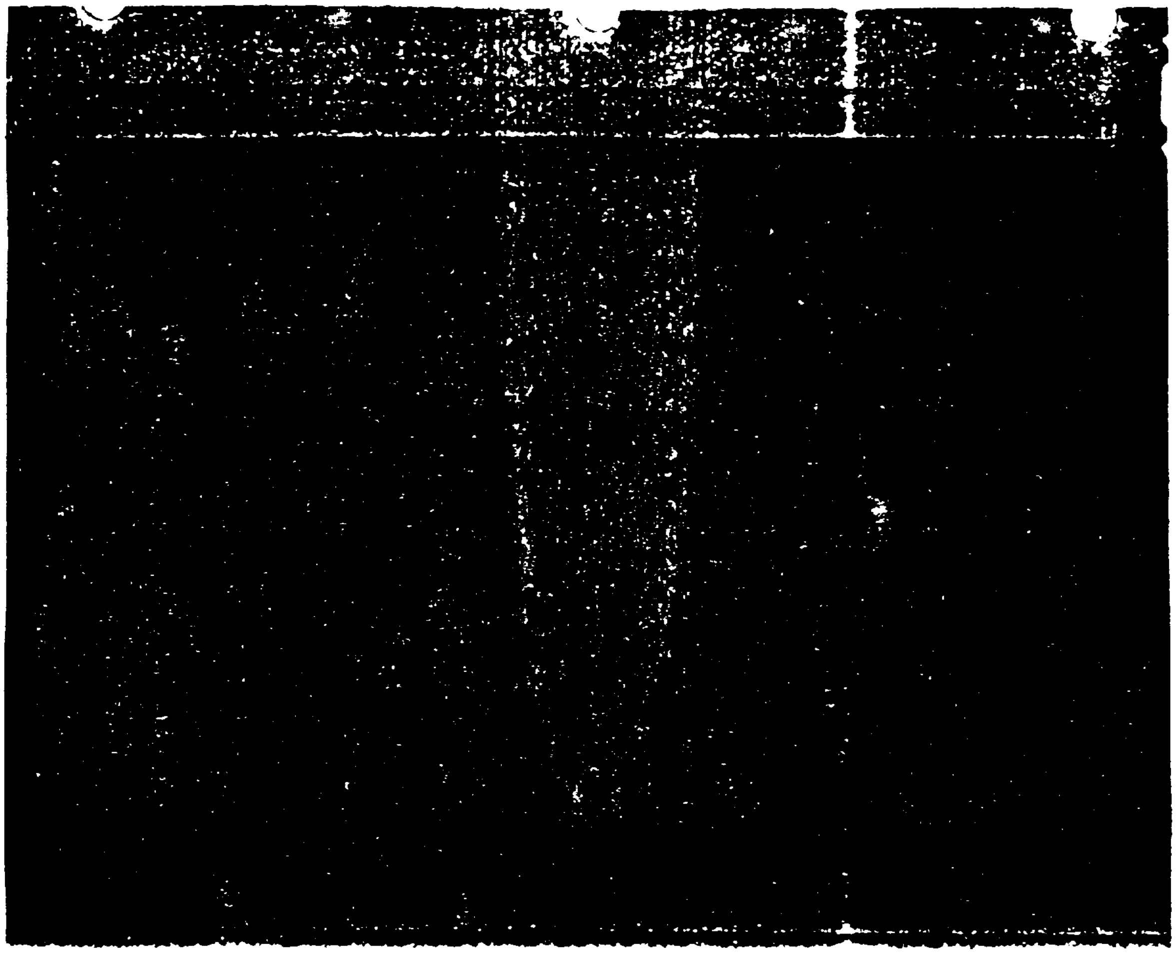
  - Lewis Research Center
  - Jet Propulsion Laboratory
  - DOE/SDIO/USAF
  - Industry/University Contracts

- AUGMENTATION

  Meets NASA's funding commitments under the MOU so that the SP-100 program can stay on schedule

- PAYOFF

  A flexible power source that can span a range of power levels up to 1 MWe for space and surface bases with improved specific mass and lifetime



SPACE ENERGY CONVERSION R&T

OAET

HIGH CAPACITY POWER

- **OBJECTIVES**

  Develop and demonstrate low-mass, reliable, long-lived power conversion technologies for space nuclear reactor power systems

- **PARTICIPANTS**

  - Lewis Research Center
  - Jet Propulsion Laboratory
  - Industry/University Contracts

- **AUGMENTATION**

  Allows development and demonstration of 1300 K Stirling conversion system (35% efficient) in time for early SEI use

- **PAYOFF**

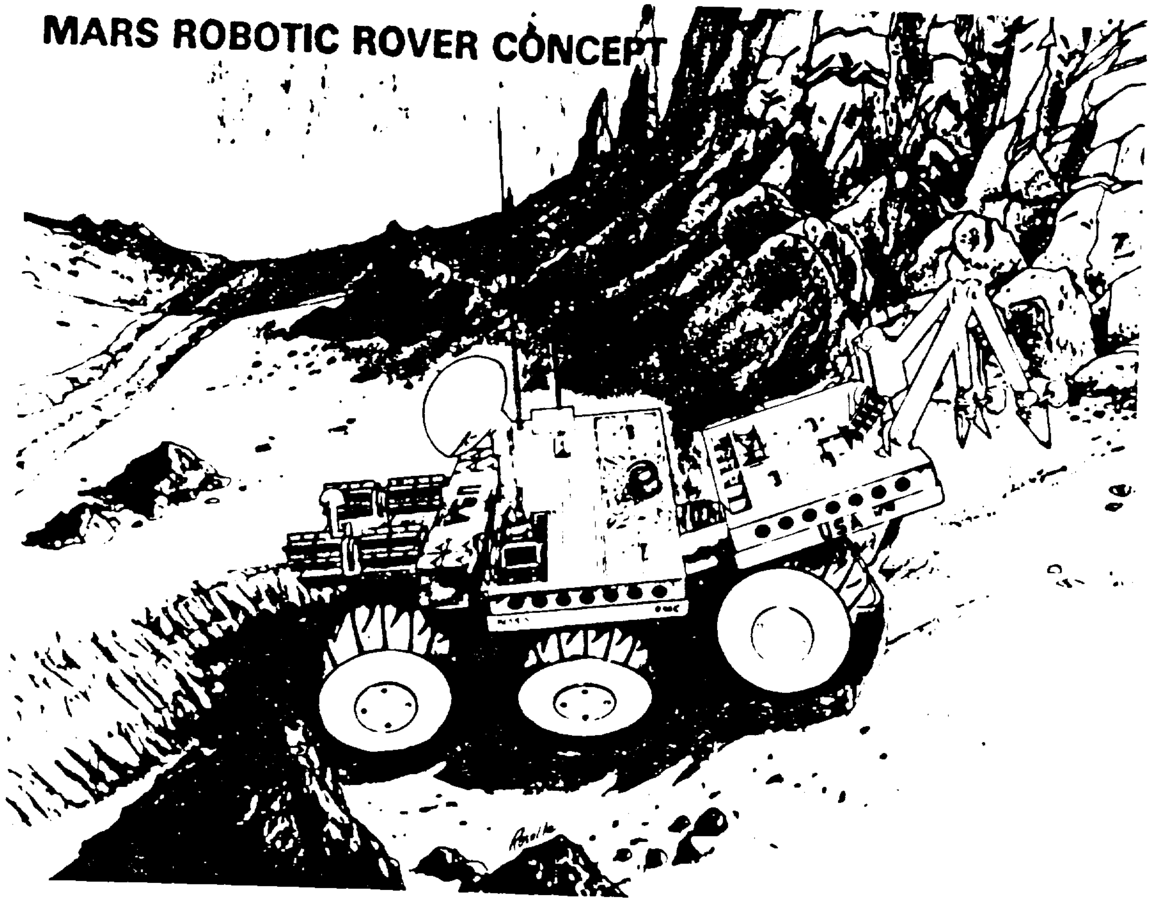
  Provides SP-100 with the conversion technology to scale up to 1 MWe

SPACE ENERGY CONVERSION R&T

OAET

SURFACE POWER & THERMAL MANAGEMENT

- OBJECTIVES
  Develop solar-based power and low-grade heat thermal management technologies to support lunar and Mars surface system operations
- PARTICIPANTS
  - Lewis Research Center
  - Jet Propulsion Laboratory
  - Johnson Space Center
  - Goddard Space Flight Center
  - Los Alamos National Laboratory
  - Industry/University Contracts
- AUGMENTATION
  Allows funding for a solar-based surface power system that will be essential to the first exploration/outpost missions and for backup
- PAYOFF
  Provides a light-weight, reliable, solar-based power system for lunar and Mars applications



SPACE ENERGY CONVERSION R&T

MOBILE SURFACE SYSTEMS (POWER)

- OBJECTIVES

  Develop compact power technologies to a level of readiness sufficient to enable mobile and portable extraterrestrial surface power systems

- PARTICIPANTS
  - Lewis Research Center
  - Jet Propulsion Laboratory
  - Johnson Space Center
  - Industry/University Contracts

- AUGMENTATION

  Reinstates mobile surface power systems program enabling work on system integration, power generation (PV and nuclear), energy storage, triboloby, PMAD, small free-piston Stirling engine, convective heat exchangers for Martian surface mobile and/or portable dynamic isotope power systems

- PAYOFF

  Provides mobile power system options that can span the range from <1 kWe to >20 kWe with varying power ratios and usages for a hostile, dusty environment.

MOBILE SURFACE SYSTEMS (POWER)
SPACE ENERGY CONVERSION R&T

OBJECTIVES

- **Programmatic**
  Develop compact power technologies to a level of readiness sufficient to enable mobile and portable extraterrestrial surface power systems
- **Technical**

Power Generation	14% efficient thermoelectric couple 30% efficient PV cell
Energy Storage	>50 W·h/kg battery >350 W·h/kg (Fuel cell @ 10 h)
PMAD	30% improvement in operating efficiency

SCHEDULE

- 1994 Recommend primary technology candidates with options
- 1996 Complete fab of bipolar Ni/H2 battery
  Mfg prototype multicouple @ Z = 0.85
- 1997 Establish preliminary design of fuel cell
  Select battery technology
- 1998 Select PMAD's fractional horsepower optimized motor/controller
- 1999 Demonstrate combined Z = 1.4 (14% eff @ 1300 K)
  Optimize efficiency of bottom cell of PV tandem cell
- 2001 Complete performance verification on modified test bed
  Dem. sliding/rolling, dust seal and lube options

RESOURCES ($M)

	Current	3X	Strategic
FY-91	3	3	3
FY-92	0	0	0
FY-93	0	0	0
FY-94	0	0	3
FY-95	0	0	3.2
FY-96	0	0	8
FY-97	0	0	10.4

PARTICIPANTS

- **Lewis Research Center**
  Lead center in all technology elements
- **Jet Propulsion Laboratory**
  Support in PV cell and array technology
  Innovative PMAD technology
  Support in battery technology
  Thermoelectric technology
- **Johnson Space Center**
  Supporting verification tests of fuel cells

SPACE ENERGY CONVERSION R&T

OAET

MOBILE SURFACE SYSTEMS (POWER)

- **TECHNOLOGY NEEDS**

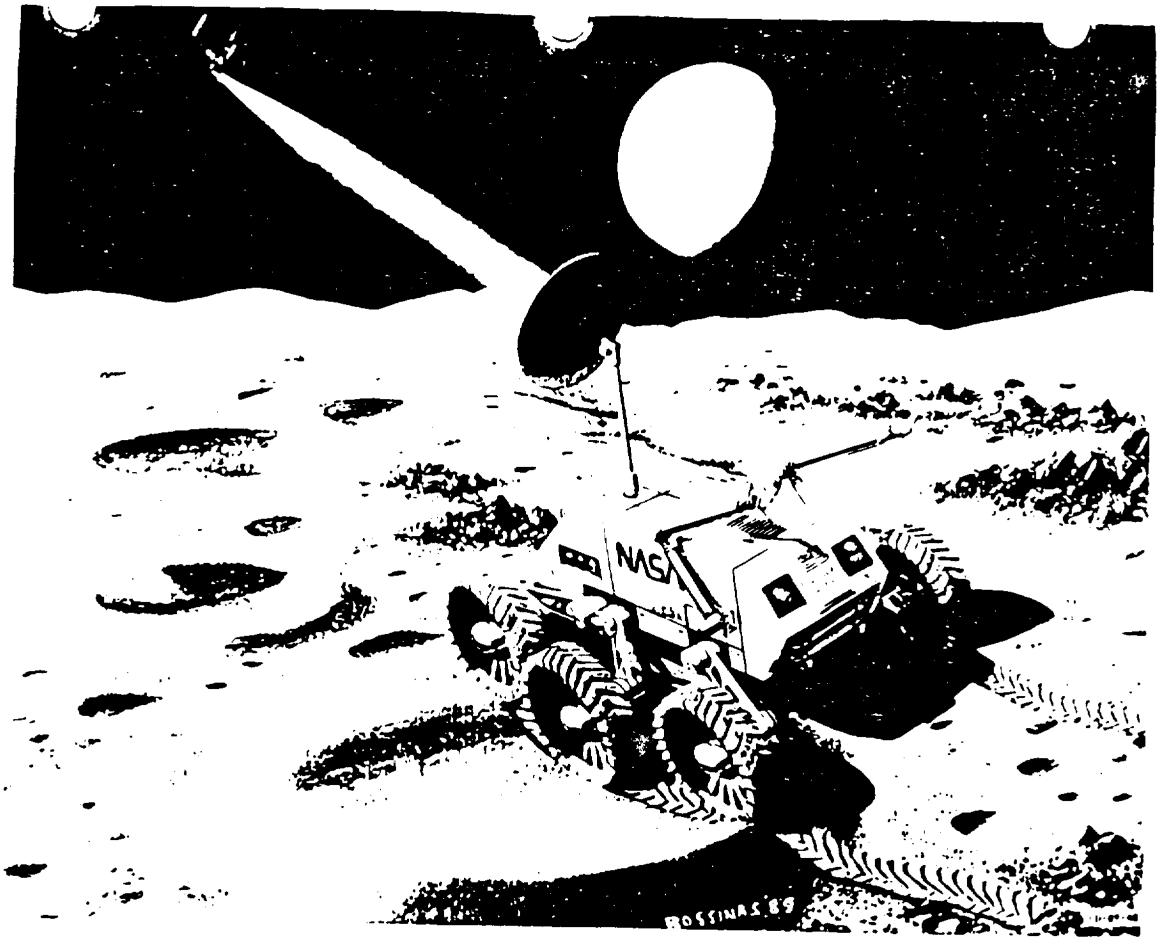
  Rover and portable extraterrestiral surface systems have been shown to require power levels ranging from <1 kWe to >20 kWe with peak-to-average power ratios >10. Mission durations vary from intermittent to continuous use in a hostile, dusty environment.

- **PROGRAMMATIC**

  Original program, Planetary Rover Project, will be terminated in FY 1992. The budget plan allows for restarting the program in FY 1994. The original power subelement of Planetary Rover was limited to improving the performance of thermoelectric materials.

- **STRATEGIC PROGRAM**

  The resources under the Strategic budget would permit system studies, focused power generation and energy storage technology, tribology, and PMAD in the relevant environment and duty cycles.



SPACE ENERGY CONVERSION R&T

OAET

LASER POWER BEAMING

- OBJECTIVES

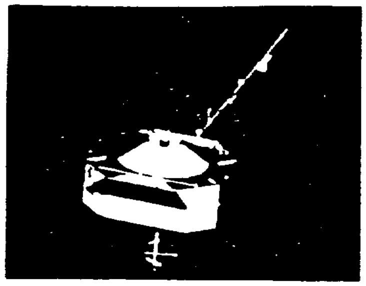
  Develop and demonstrate the technologies and subsystems for laser power beaming from Earth to Moon
- PARTICIPANTS
  - Jet Propulsion Laboratory
  - Lewis Research Center
  - Marshall Space Flight Center
  - MIT Lincoln Lab/LLNL/Industry/University Contracts
- AUGMENTATION

  Initiates a new thrust to develop the technologies (free electron laser/optics/PV/PMAD) to enable an advanced power supply systems
- PAYOFF

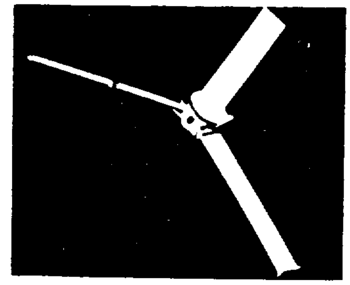
  Provides a revolutionary way to power lunar surface bases and rovers with greatly reduced mass and launches.

NASA

PLANETARY ORBITERS
(MERCURY ORBITER)



MISSIONS TO COMETS (COMET NUCLEUS SAMPLE RETURN TAIL PROBE)



MARS ROVER

PENETRATORS
(GLOBAL NETWORK MISSION)

SPACE ENERGY CONVERSION R&T

OAET

SPACECRAFT POWER AND THERMAL MANAGEMENT

- OBJECTIVES

  Develop and demonstrate integrated spacecraft bus technologies for deep space applications

- PARTICIPANTS
  - Jet Propulsion Laboratory
  - Lewis Research Center
  - Goddard Space Flight Center
  - Industry/University Contracts

- AUGMENTATION

  Initiates a new thrust to (1) demonstrate high power density solar array with deployment and LILT resistant; (2) develop advance static or dynamic conversion systems for radioisotope sources; define integration issues/advantages of reactor-powered science spacecraft; (3) develop energy storage for penetrators; (4) develop advanced PMAC and thermal management for deep space missions

- PAYOFF

  Provides high specific power solar arrays and high efficiency converters with advanced PMAC and energy storage to reduce mass and/or increase power of deep space missions

SPACECRAFT POWER AND THERMAL MANAGEMENT
SPACE ENERGY CONVERSION R&T

OBJECTIVES

- **Programmatic**
  Develop and demonstrate integrated spacecraft bus technologies for deep space applications including both PV and nuclear power sources
- **Technical**
  - Assess advantages and issues of reactor power systems
  - Reduce PV array mass by 5X
  - Reduce radioisotope inventory by up to 4X
  - Provide autonomous reconfigurable power system with 2X mass reduction, 75% parts reduction
  - Reduce radiator mass and area by 2X
  - Develop advanced, integrated sensor cooling technology
  - Extend life (2 - 3X) and impact capability of primary batteries

SCHEDULE

- 1994 Select radioisotope power technology
  Select advanced bus regulator (hybrid components)
- 1996 Demonstrate 300+ W/kg planar PV blanket
  Design primary battery structure
- 1997 Demonstrate reactor integration, issues and potential advantages
  Flight test advanced cryo heat pipes
  Dem adv. radioisotope conversion module
  Dem eng load power converter (hybrid comp.)
- 1998 Dem light-weight radiator tech & primary batteries
  Dem low noise instrument power converter using hybrid components
- 1999 Dem integrability of advanced power conversion module with radioisotope power source and 10-year life capability (modeling)

RESOURCES ($M)

	Current	3X	Strategic
FY-91	0	0	0
FY-92	0	0	0
FY-93	0	0	2
FY-94	0	0	3.5
FY-95	0	0	6
FY-96	0	0	7.5
FY-97	0	0	9.1

PARTICIPANTS

- **Jet Propulsion Laboratory**
  Light-weight planar PV array and power integrated circuits (PICs); mission impact assessments; static conversion systems for radioisotope power sources
- **Lewis Research Center**
  Autonomous PMAC subsystems; dynamic conversion technologies for radioisotope power sources, nuclear reactor analyses; moderate and high temperature radiators; and thin film photovoltaics
- **Goddard Space Flight Center**
  Low temperature thermal management subsystems

SPACE ENERGY CONVERSION R&T

OAET

SPACECRAFT POWER & THERMAL MANAGEMENT

- **TECHNOLOGY NEEDS**

  Deep space missions will require reduced radioisotope mass (cost/availability issue) and/or improved performance from photovoltaic arrays (low light/low temperature issue). Inner solar system spacecraft will need high-temperature-resistant arrays. All require lower PMAD mass, battery mass, and radiator mass.

- **PROGRAMMATIC**

  The ongoing R&T Base program is generically focused since resources do not permit covering all types of spacecraft. Currently there is no focused technology on assessing, developing, or demonstrating power technologies for deep space missions.

- **STRATEGIC PROGRAM**

  The resources under the Strategic budget would focus on increased radioisotope-based system efficiency (reduces fuel requirements and cost). These resources would enable extending the range of photovoltaic capabilities (<1 AU to ~5 AU). In parallel, these resources would enable similar operational environment extensions for the other power system components.

SPACE ENERGY CONVERSION R&T

OAET

EARTH ORBIT PLATFORM POWER & THERMAL MANAGEMENT

- OBJECTIVES

  Develop and demonstrate integrated power and thermal management technologies for near-Earth missions.

- PARTICIPANTS
  - Lewis Research Center
  - Jet Propulsion Laboratory
  - Goddard Space Flight Center
  - Industry/University Contracts

- AUGMENTATION

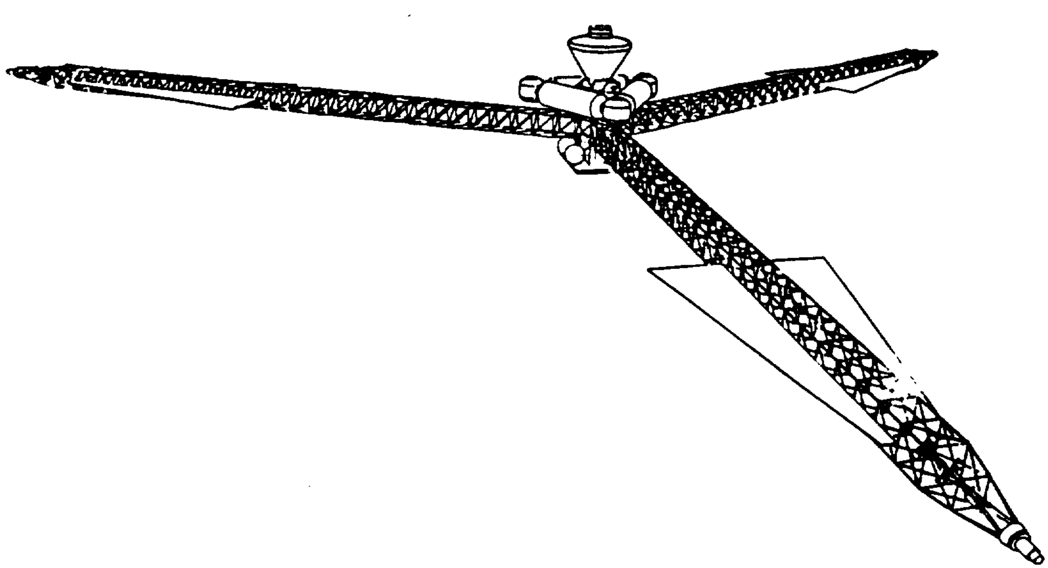
  Initiates a new thrust to develop planar and concentrator arrays immune to the space environment with 100 W-h/kg battery systems, integrated, high-efficiency autonomous PMAC, and integrated thermal management for high-temperature electronics

- PAYOFF

  Provides a 300 W/kg PV blanket; 100 W/kg InP concentrator module, a 100 W-h/kg battery (flight weight), 1 - 2 kg/m2 thermal management system with advanced PMAC integrated system and durable high temperature electronics subsystem

NASA NUCLEAR PROPULSION PROGRAM OAET

Possible Nuclear Electric Propulsion Concept for Advanced Space Missions



Program Goals

- Develop the technologies required to apply space nuclear propulsion systems to improve the mission performance for human missions to Mars

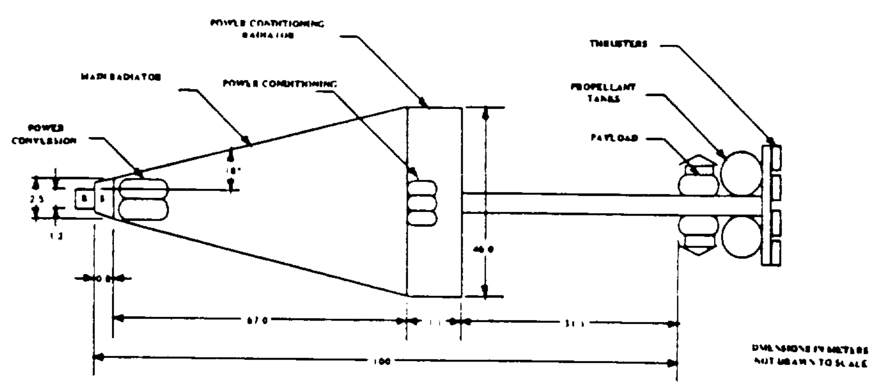
- Identify and develop at least one space nuclear thermal propulsion system and one nuclear electric propulsion system that, alone or in combination with other propulsion systems, meets the propulsion requirements for piloted and cargo missions to Mars (including unmanned precursor missions) and for which technical feasibility issues have been resolved

NUCLEAR PROPULSION

NUCLEAR THERMAL PROPULSION | NUCLEAR ELECTRIC PROPULSION

NUCLEAR ELECTRIC PROPULSION

The generic nuclear electric propulsion (NEP) system uses a nuclear reactor to produce electrical power which is then used to operate low-thrust electromagnetic thrusters (such as ion thrusters or magnetoplasmadynamic thrusters). The advantage of NEP is that the specific impulse is increased by a factor of at least 10 and perhaps 20 compared to chemical propulsion which can result in a significant reduction (factor of ~2) of the mass into low Earth orbit. Combined with a high-thrust option (either chemical or nuclear thermal propulsion) it can achieve the same transit times as nuclear thermal propulsion.



Basic Features of a Nuclear Electric Propulsion System

NASA NUCLEAR PROPULS N PROGRAM OAET

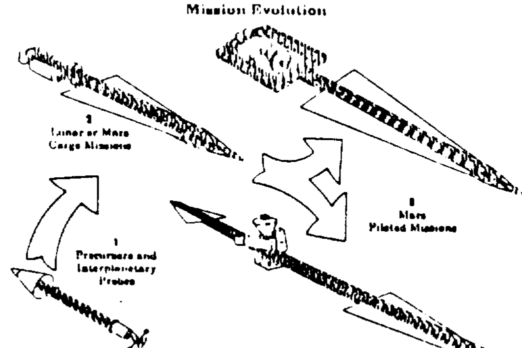
NEP EVOLUTION POTENTIAL

- NEP MAY EVOLVE FROM kWe POWER LEVELS (SP-100) TO MULTI-MWe POWER LEVELS
- NEAR TERM NEP TECHNOLOGY MAY BE APPLIED TO UNMANNED PLANETARY MISSIONS (e.g. OUTER PLANETS, ASTEROIDS, COMETS) WHICH HAVE HIGH SCIENTIFIC RETURN AS WELL AS LAYING A FOUNDATION FOR THE NEXT STEP OF EVOLUTION
  - HIGHLY ENERGETIC MISSIONS CAN BE PERFORMED WITH NEAR TERM NEP TECHNOLOGY

Characteristics of Nuclear Electric Propulsion

- Powers range from kWe to multi-MWe
- High specific impulse
  - Same thruster can operate at range of specific impulses
  - Reduces propellant mass
  - Decreased resupply and refurbishment masses
- Long system life
  - High level of reusability
- Enhanced flexibility
  - Extended launch window
  - Same vehicle used for multiple opportunities
- Commonality with surface power systems

Mission Evolution



NASA NUCLEAR PROPULSION PROGRAM OAET

UNMANNED EXPLORATION MISSIONS
(POTENTIAL)

MISSION	LAUNCH	DURATION	NEP APPLICABILITY
Main Belt Asteroid	~2000	10 years	Enhancing
Asteroid Sample Return	~2000	5 years	Enhancing (Possibly enabling)
Jovian Grand Tour	Post 2000	Variable	Enabling
Saturn Grand Tour	Post 2000	Variable	Enabling
Thousand Astronomical Unit (TAU)	Post 2010	55+ years	Enabling
Comet Nucleus Sample Return	Post 2000	6 years	Enhancing (Possibly enabling)

NASA NUCLEAR PROPULSION STATUS OAET

NUCLEAR ELECTRIC PROPULSION HIGH-PRIORITY NEAR-TERM TECHNOLOGIES (Identified by Reactor and Propulsion Subpanels)

PROPULSION

- SCALING TO HIGHER POWER
  - Ion Thrusters/MPD Thrusters
- FACILITY UPGRADES
  - Thermal Management/Pumping
- HIGH-TEMPERATURE POWER PROCESSING

POWER

- HIGH-TEMPERATURE, LIGHT-WEIGHT RADIATORS
- HIGH-TEMP, RAD-HARDENED POWER ELECTRONICS
- SYSTEM INTEGRATION, COMPONENT INTERACTION

KEY ISSUE: INCREASE SPECIFIC POWER (kW/kg)

Coordination and Interfaces

COORDINATION/INTERFACES

The following is a list of some of the coordination and interfaces involving the NASA Space Energy Conversion R&T Program

Space Technology Interface Group (STIG) (NASA/USAF)

Interagency Advanced Power Group

Space Photovoltaic Research & Technology (SPRAT) Conference

Space Electrochemical Research & Technology (SERT) Conference

High-Frequency Power Distribution Control Conference

Radioisotope Power Systems Requirements Workshop

Aerospace Battery Systems Steering Committee/Battery Workshop/Systems Review

SP-100 Steering Committee (SDIO/DOE/USAF/NASA)

SDIO Independent Evaluation Group and Field Support Team

DoD Advisory/Review Panels (AFSTC Investment Strategy, SPT-21, Thermionic Advisory Team, Thermal Management Steering Committee, Space Power Technology Interdependency Group)

Program Office/Industry Briefings
- Earth Observing System (EOS)
- ATDRSS

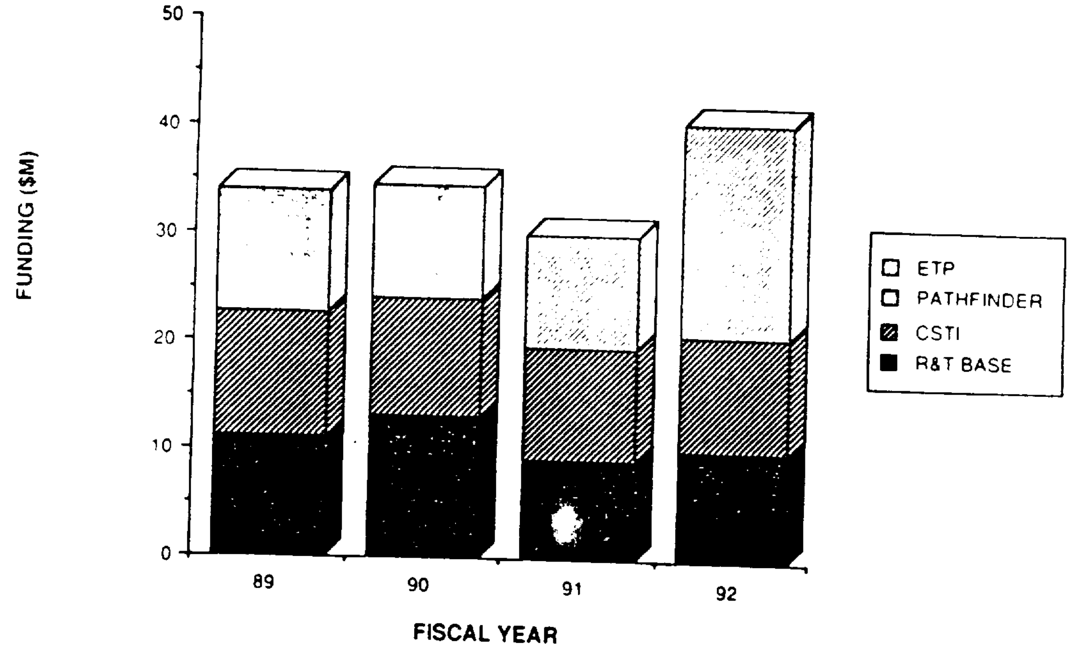
Nuclear Propulsion (DoD/DOE/NASA)

National Meetings (IECEC, SNPS, etc.)

Budgets

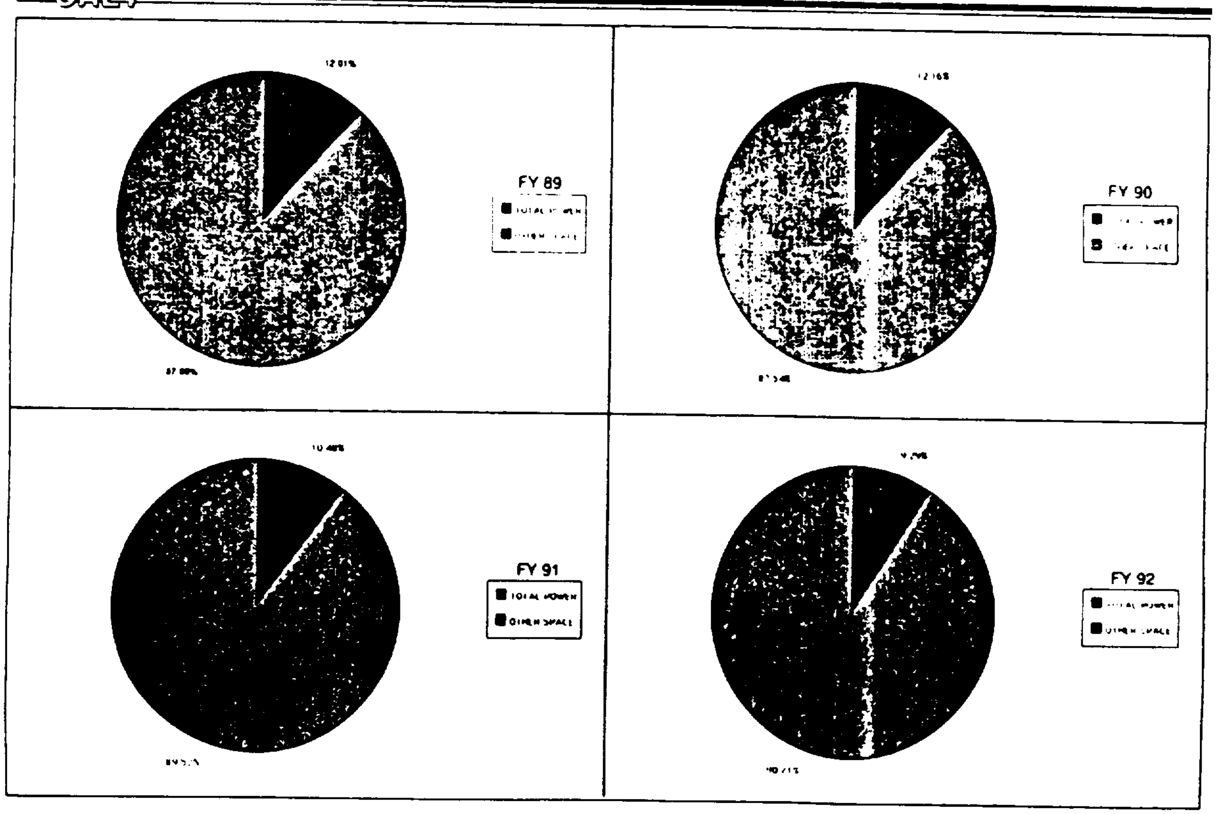
POWER FUNDING TREND

OAET



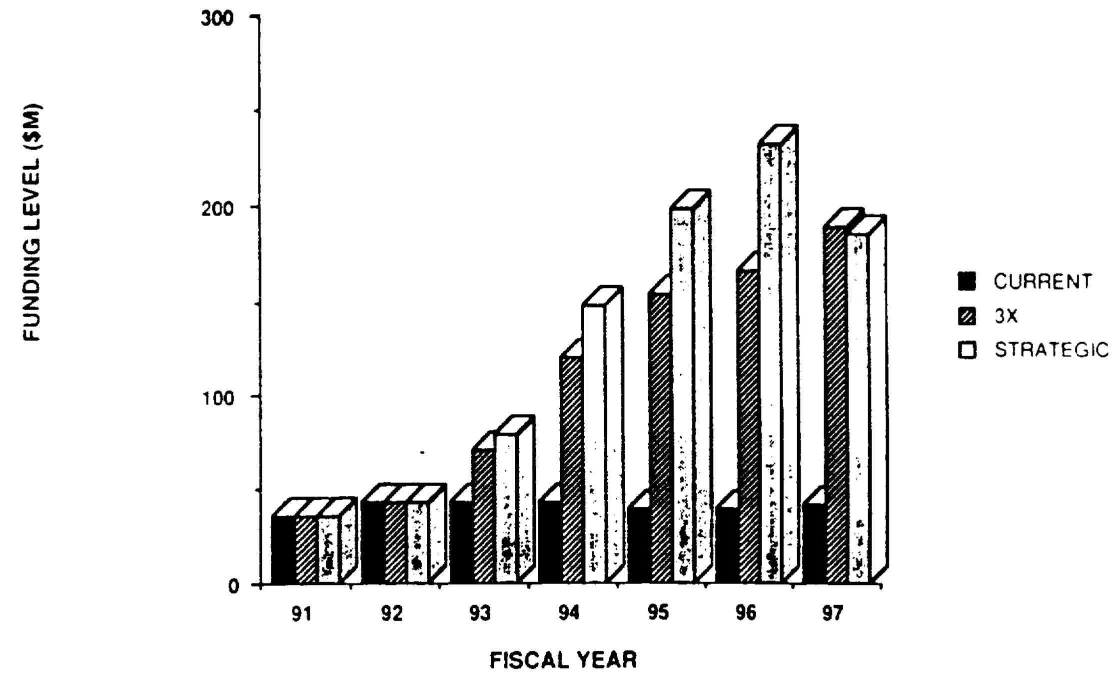
POWER FUNDING TREND
AS % OF TOTAL SPACE R&D FUNDING

OAET



TOTAL SPACE ENERGY CONVERSION TECHNOLOGY

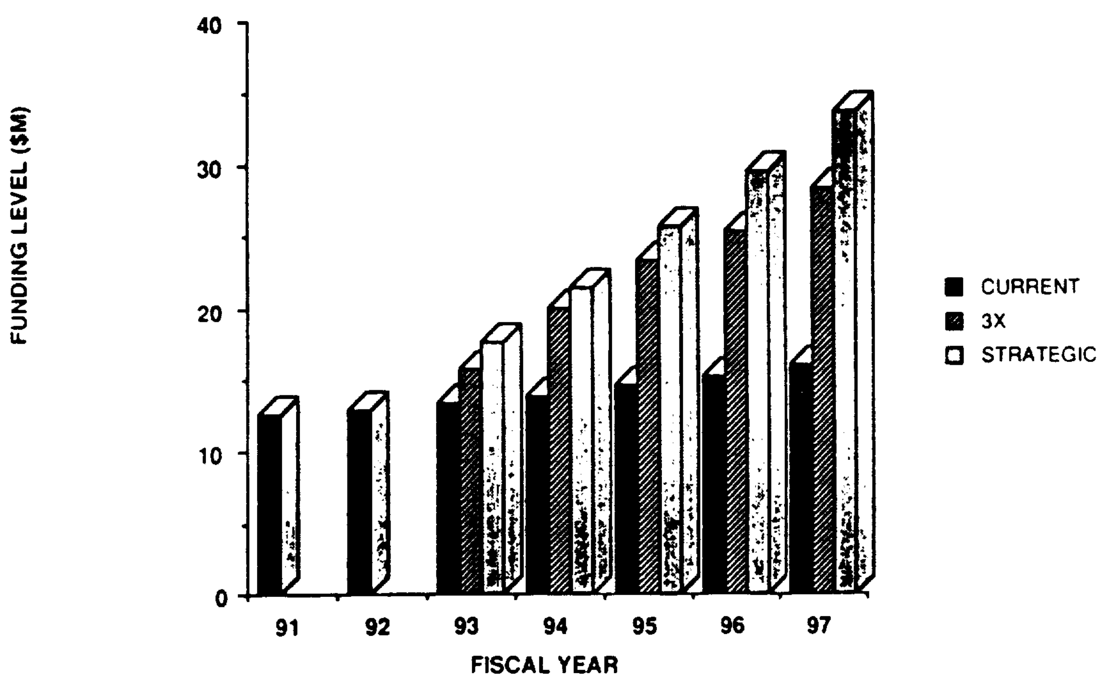
OAET



BASE RESEARCH AND TECHNOLOGY PROGRAM

SPACE ENERGY CONVERSION TECHNOLOGY

OAET



WBS No. 506-41 (CURRENT BUDGET)

REVISED

TECHNOLOGY ELEMENT:	POWER R&T	WBS 506-41	CODE RP

Sub-Element Resources: ($M)	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002
-11 Photovoltaic Energy Conversion	2.4*	2.3	2.4	2.5	2.6	2.7	2.8					
-21 Chemical Energy Conversion	1.8	2.0	2.1	2.2	2.3	2.4	2.5					
-31 Thermal Energy Conversion	1.7	1.4	1.5	1.6	1.7	1.8	1.9					
-41 Power Management	2.0	1.8	1.9	2.0	2.1	2.2	2.3					
-51 Thermal Management	0.7	1.0	1.0	1.1	1.1	1.2	1.2					
Sub-Element Totals: ($M)	8.6	8.5	8.9	9.4	9.8	10.3	10.7					
CoF:												
CoF Totals:												
Resources Requirements: ($M)	8.6	8.5	8.9	9.4	9.8	10.3	10.7					
Program Support: ($M)	1.7	1.8	2.0	2.1	2.3	2.4	2.6					
Special Requirements: ($M)	2.2	2.5	2.4	2.3	2.5	2.6	2.7					
TOTAL ($M):	12.5*	12.8	13.3	13.8	14.6	15.3	16.0					

Basis for Resource Estimates:

- Maintain current funding levels; adjust for inflation.

* *Includes $1M carried over from FY90*

WBS No. 506-41 ("3X" BUDGET)

REVISED

TECHNOLOGY ELEMENT:	POWER R&T	WBS 506-41	CODE RP

Sub-Element Resources: ($M)	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002
-11 Photovoltaic Energy Conversion	2.4*	2.3	3.4	5.8	7.2	7.5	8.3					
-21 Chemical Energy Conversion	1.8	2.0	2.9	3.5	3.9	4.4	5.0					
-31 Thermal Energy Conversion	1.7	1.4	1.9	2.1	2.4	2.7	3.0					
-41 Power Management	2.0	1.8	2.9	3.3	3.7	4.1	4.6					
-51 Thermal Management	0.7	1.0	1.1	1.4	1.7	1.9	2.3					
Sub-Element Totals: ($M)	8.6	8.5	12.2	16.1	18.9	20.6	23.2					
CoF:												
CoF Totals:												
Resources Requirements: ($M)	8.6	8.5	12.2	16.1	18.9	20.6	23.2					
Program Support: ($M)	1.7	1.8	1.8	2.0	2.3	2.6	2.8					
Special Requirements: ($M)	2.2	2.5	1.8	2.0	2.2	2.4	2.6					
TOTAL ($M):	12.5*	12.8	15.8	20.1	23.4	25.6	28.6					

Basis for Resource Estimates:

- Grow photovoltaic and associated chemical energy storage and power management technologies to make dramatic reductions in spacecraft mass allocated to power.
- Maintain a supporting base activity in thermal energy conversion and thermal management.
- Insufficient resources to develop an advanced concepts technology program as a separate sub-element program. Advanced concepts will be worked in the existing sub-elements.

* *Includes $1M carried over from FY90*

WBS No. 506-41 (STRATEGIC BUDGET)

REVISED 6/1/91

TECHNOLOGY ELEMENT:	POWER R&T				WBS 506-41			CODE RP				
Sub-Element Resources: ($M)	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002
-11 Photovoltaic Energy Conversion	2.4*	2.3	3.3	4.6	5.9	7.2	8.5					
-21 Chemical Energy Conversion	1.8	2.0	2.8	3.4	3.9	4.4	5.0					
-31 Thermal Energy Conversion	1.7	1.4	1.8	2.1	2.4	2.7	3.0					
-41 Power Management	2.0	1.8	2.8	3.2	3.7	4.1	4.6					
-51 Thermal Management	0.7	1.0	1.1	1.4	1.7	1.9	2.3					
-91 Advanced Concepts	0.0	0.0	2.1	2.4	3.2	3.8	4.3					
Sub-Element Totals: ($M)	8.6	8.5	13.9	17.1	20.8	24.1	27.7					
CoF:												
CoF Totals:												
Resources Requirements: ($M)	8.6	8.5	13.9	17.1	20.8	24.1	27.7					
Program Support: ($M)	1.7	1.8	1.8	2.2	2.6	3.0	3.4					
Special Requirements: ($M)	2.2	2.5	2.0	2.2	2.4	2.6	2.8					
TOTAL ($M):	12.5*	12.8	17.7	21.5	25.8	29.7	33.9					

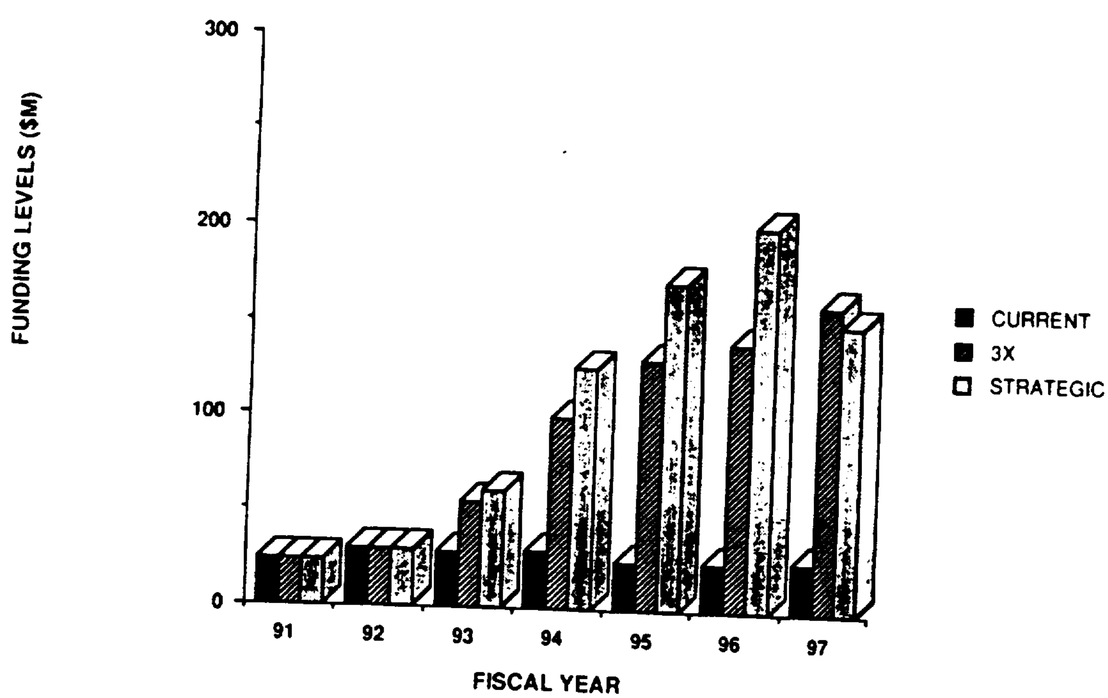
Basis for Resource Estimates:

- Grow photovoltaic and associated chemical energy storage and power management technologies to make dramatic reductions in spacecraft mass allocated to power.
- Develop advanced concepts program to permit development of innovative technologies that promise revolutionary improvements in performance.
- Maintain a supporting base activity in thermal energy conversion and thermal management.
- *Includes $1M carried over from FY90*

FOCUSED TECHNOLOGY PROGRAM

SPACE ENERGY CONVERSION TECHNOLOGY

OAET



FOCUSED TECHNOLOGY PROGRAMS
SPACE ENERGY CONVERSION R&T

OAET

CURRENT BUDGET

PROGRAM ELEMENT	FY91	FY92	FY93	FY94	FY95	FY96	FY97
SPACE NUCLEAR POWER	10	20	25	25	20	20	20.9
HIGH CAPACITY POWER	10.4	10.6	4.5	4.6	4.8	5	5.2
SURFACE POWER & THERMAL MANAGEMENT	0.6	0	0	0	0	0	0
MOBILE SURFACE SYSTEMS	3	0	0	0	0	0	0
LASER POWER BEAMING	0	0	0	0	0	0	0
EARTH ORBITING PLATFORM POWER & THERMAL MANAGEMENT	0	0	0	0	0	0	0
SPACECRAFT POWER & THERMAL MANAGEMENT	0	0	0	0	0	0	0
TOTAL	24	30.6	29.5	29.6	24.8	25	26.1

Basis for Resource Estimates: Maintain current funding levels

FOCUSED TECHNOLOGY PROGRAMS
SPACE ENERGY CONVERSION R&T

OAET

"3X" BUDGET

PROGRAM ELEMENT	FY91	FY92	FY93	FY94	FY95	FY96	FY97
SPACE NUCLEAR POWER	10	20	25	25	26	27	28
HIGH CAPACITY POWER	10.4	10.6	10.9	12	12.3	12.6	18
SURFACE POWER & THERMAL MANAGEMENT	0.6	0	3.4	9	12.6	14	18
MOBILE SURFACE SYSTEMS	3	0	0	0	0	0	0
LASER POWER BEAMING	0	0	8	40	64.3	70	75
EARTH ORBITING PLATFORM POWER & THERMAL MANAGEMENT	0	0	3.5	6.5	7.5	8	10
SPACECRAFT POWER & THERMAL MANAGEMENT	0	0	0	0	0	0	0
TOTAL	24	30.6	55.6	100.5	131.1	140.5	161

Basis for Resource Estimates: Grow Surf. Pwr/Laser Beaming/E-0 Platforms to make dramatic reductions in spacecraft mass allocated to power

SPACE ENERGY CONVERSION R&T

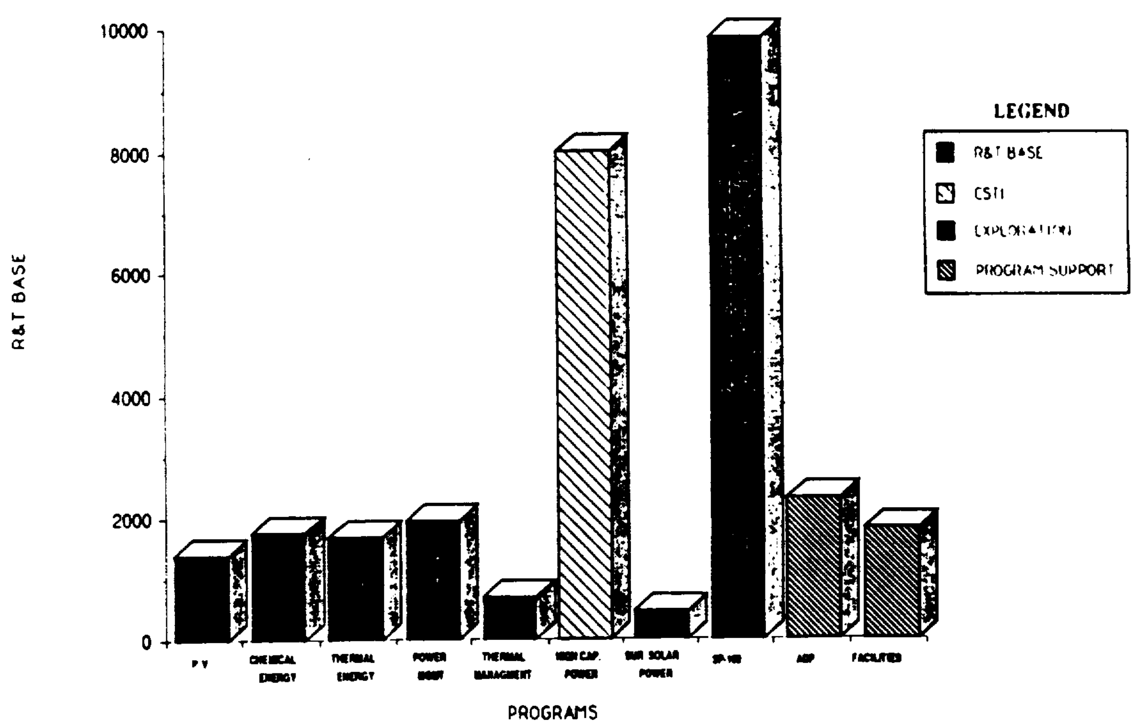
STRATEGIC BUDGET

PROGRAM ELEMENT	FY91	FY92	FY93	FY94	FY95	FY96	FY97
SPACE NUCLEAR POWER	10	20	25	25	26	27	28
HIGH CAPACITY POWER	10.4	10.6	11.1	16.8	23	30.5	23
SURFACE POWER & THERMAL MANAGEMENT	0.6	0	5	11.7	18.5	24.2	25.3
MOBILE SURFACE SYSTEMS	3	0	0	3	3.2	8	10.4
LASER POWER BEAMING	0	0	13.5	56.9	82.5	90.8	41
EARTH ORBITING PLATFORM POWER & THERMAL MANAGEMENT	0	0	5.1	10.2	13.5	14.3	14.7
SPACECRAFT POWER & THERMAL MANAGEMENT	0	0	2	3.5	6	7.5	9.1
TOTAL	24	30.6	61.7	127.1	172.7	202.3	151.5

Basis for Resource Estimates: Grow Surf. Pwr/Laser Beaming/E-0 & SC Platforms/Hi Capacity Pwr to make dramatic reductions in platform/base power mass (or increased power)

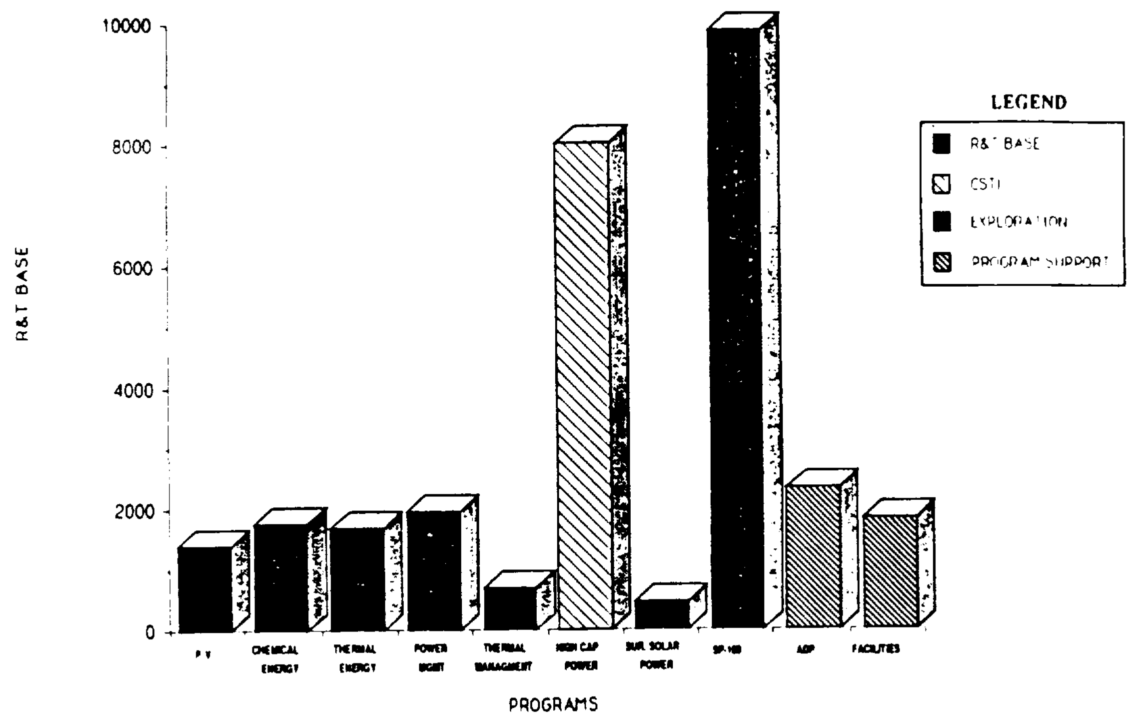
CODE RP POWER FUNDING

POWER FUNDS DISTRIBUTION FOR FY 91



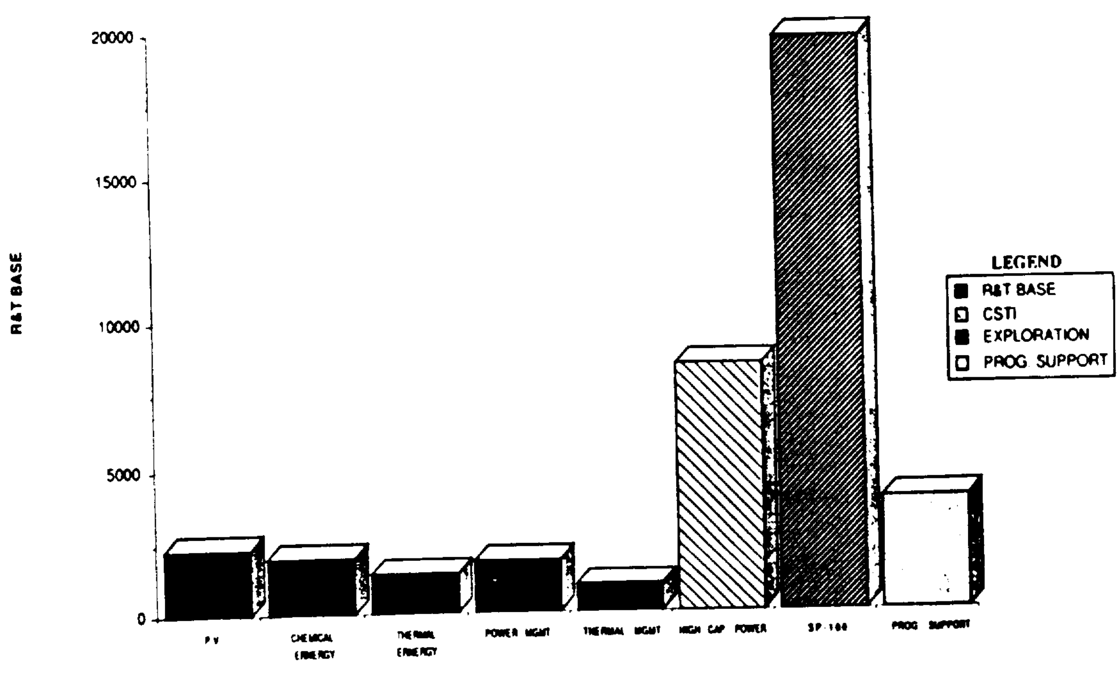
CODE RP POWER FUNDING

POWER FUNDS DISTRIBUTION FOR FY 91



CODE RP POWER FUNDING

POWER FUNDS DISTRIBUTION FOR FY 92



Summary

SPACE ENERGY CONVERSION R&T

SUMMARY

OAET

- TECHNICAL CHALLENGE

  To make a 2X to >10X improvement in the performance of space power systems (specific power/energy, efficiency, lifetime, reliability, etc.)
  To enable a wide range of future space missions while holding the power mass fraction at or below today's technology

- APPROACH

  Develop lighter, more efficient primary power sources and energy storage systems with lighter, more reliable, more compact power management & control with innovative thermal management and power distribution.

- PAYOFF

  This technology will enable future missions to provide the same power at greatly reduced mass or more power from the same mass. More importantly, this technology will enable a host of future SEI and other space missions.

- RATIONALE FOR AUGMENTATION

  These resources will allow the base technology to be moved out of the laboratory and demonstrated to a degree that users can take it over. These resources will permit work on new technologies focused on future space missions.

- RELATIONSHIP TO OTHER PROGRAMS

  This work is closely coupled (base + focused) and is well coordinated with other agencies and users.

- TECHNOLOGY CONTRIBUTIONS

  SSF (PV,NiH2,SD, Env.), HST (NiH2), EOS (PV,NiH2, Therm. mgmt), DoD (NiH2), GaAs, USAF (Li primary)

External Review Process

INTEGRATED TECHNOLOGY PLAN FOR THE CIVIL SPACE PROGRAM

EXTERNAL REVIEW APPROACH

OAET

OBJECTIVES

"NASA (SHOULD) UTILIZE AN EXPERT, OUTSIDE REVIEW PROCESS, MANAGED FROM HEADQUARTERS, TO ASSIST IN THE ALLOCATION OF TECHNOLOGY FUNDS"

- REVIEW THE PROCESS USED FOR DEVELOPING THE INTEGRATED TECHNOLOGY PLAN FOR THE CIVIL SPACE PROGRAM
- ASSESS THE TECHNICAL CONTENT OF THE PROPOSED ITP
  - IDENTIFY KEY TECHNOLOGY AREAS THAT NEED TO BE ADDRESSED
  - FIRST-ORDER EVALUATION OF THE ESTIMATES OF "COST FOR ACCOMPLISHMENT"
  - RECOMMEND ADJUSTMENTS IN PRIORITIES AND RESOURCE PLANNING
- ASSESS THE ACCOMMODATION OF USER NEEDS
  - EVALUATE STRATEGIC AND NEAR-TERM TECHNOLOGY PLANS AGAINST TECHNOLOGY NEEDS OF FUTURE MISSIONS
  - RECOMMEND POTENTIAL CHANGES IN THE PHASING OF NEW PROGRAMS TO BETTER MEET TECHNOLOGY NEEDS

MAY 13, 1991
JCM 7461

INTEGRATED TECHNOLOGY PLAN FOR THE CIVIL SPACE PROGRAM

ITP EXTERNAL REVIEW PLANNING

OAET — *PRELIMINARY*

DETAILED REVIEW APPROACH

- PROVIDE OVERVIEWS IN PLENARY SESSION PRESENTATIONS
  - MISSION USER TECHNOLOGY NEEDS AND APPLICATIONS
  - EXTERNAL PERSPECTIVES ON SPACE TECHNOLOGY
  - STRATEGIC OVERVIEW OF INTEGRATED TECHNOLOGY PLAN
- REVIEW THRUSTs PLENARY SESSION
  - SCIENCE, EXPLORATION, TRANSPORTATION, PLATFORMS, & OPERATIONS
- CONDUCT IN-DEPTH REVIEWS AGAINST VERTICALLY-INTEGRATED DISCIPLINE RESEARCH AREAS
  - PARALLEL TO 1987 ASEB STUDY APPROACH
  - ASSESS PLANS/DEVELOP RECOMMENDATIONS USING PANEL CHAIRMAN & RECORDING SECRETARY APPROACH
- CONDUCT SELECTED REVIEWS IN ADDITIONAL SPECIAL TOPIC AREAS
  - RESEARCH AREAS, MANAGEMENT TOPICS
  - ASSESS PLANS/DEVELOP RECOMMENDATIONS USING PANEL CHAIRMAN & RECORDING SECRETARY APPROACH
- CONDUCT DETAILED REVIEW DISCUSSIONS IN AD HOC SESSIONS, TO BE DETERMINED AT THE MEETING; COORDINATE AND REPORT WORKING GROUP RESULTS THROUGH PLENARY SESSION
- DEVELOP SUMMARY RECOMMENDATIONS IN STEERING COMMITTEE SESSION(S)

JUNE
JCM

INTEGRATED TECHNOLOGY PLAN FOR THE CIVIL SPACE PROGRAM

EXTERNAL REVIEW APPROACH

OAET

PRODUCT

A FORMAL REVIEW REPORT, TO BE PUBLISHED WITHIN 60 DAYS OF THE END OF THE MEETING

- PROGRAMMATIC RECOMMENDATIONS AND/OR ASSESSMENTS REGARDING DISCIPLINE AREAS (INCLUDING BOTH BASE AND FOCUSED PROGRAMS)
  - WHAT ARE THE RIGHT RESEARCH ISSUES, ARE THEY BEING ADDRESSED?
  - WHAT IS THE RIGHT LEVEL OF INVESTMENT, IS IT PROVIDED FOR IN THE ITP?
  - WHAT IS THE RIGHT BALANCE OF RESOURCES ACROSS THE ELEMENTS IN THE AREA (I.E., WHAT ARE THE RIGHT PRIORITIES AND WHY?)
- PROGRAMMATIC RECOMMENDATIONS AND/OR ASSESSMENTS REGARDING TECHNOLOGY THRUSTS
  - WHAT ARE THE RIGHT MISSION NEEDS, ARE THEY BEING ADDRESSED?
  - WHAT IS THE RIGHT LEVEL OF INVESTMENT, IS IT PROVIDED FOR IN THE ITP?
  - WHAT IS THE RIGHT BALANCE OF RESOURCES ACROSS THE ELEMENTS IN THE THRUST? (I.E., WHAT ARE THE RIGHT PRIORITIES AND WHY?)
- PROGRAMMATIC RECOMMENDATIONS AND/OR ASSESSMENTS FOR THE OVERALL PROGRAM
  - ARE THE RIGHT RESEARCH ISSUES AND MISSION NEEDS BEING ADDRESSED?
  - WHAT IS THE RIGHT LEVEL OF INVESTMENT, IS IT PROVIDED FOR IN THE ITP?
  - WHAT IS THE RIGHT BALANCE OF RESOURCES ACROSS THE THRUSTS AND IN THE R&T BASE? (I.E., WHAT ARE THE RIGHT PRIORITIES AND WHY?)

MAY 14 1991
JCM 7465

REVIEW QUESTIONS

- Is the program content/approach correct?
- Is the level of investment correct?
- Given the available funding are the priorities correct?
- Is the user interface functioning properly?
- Are the efforts being properly coordinated?
- Are the user needs being met?
- Are the participants correct?
- Is the R&T Base content innovative enough to provide improved capability for future user/mission applications?
- Does the R&T Base activity maintain or enhance NASA's technical capabilities?

Backup Material

SPACE ENERGY CONVERSION BASE R&T

PHOTOVOLTAIC ENERGY CONVERSION

TECHNOLOGY NEEDS

- THE HIGH PERFORMANCE PHOTOVOLTAIC ENERGY CONVERSION PROGRAM WILL DEVELOP TECHNOLOGY THAT CAN SUPPORT A WIDE RANGE OF EARTH ORBITING AND INTERPLANETARY MISSIONS INCLUDING:
    - SPACE STATION
        - REDUCES ARRAY AREA BY $\geq 1/2$
    - EARTH OBSERVING SYSTEM
        - LONG LIFE, LIGHT-WEIGHT, RADIATION-HARD ARRAY
    - LUNAR/MARS SURFACE POWER
        - COMPACT, TRANSPORTABLE ARRAYS
    - ELECTRIC PROPULSION
        - LEO-GEO AND INTERPLANETARY
    - COMMUNICATIONS SATELLITES
    - ALL NEAR-EARTH MISSIONS

SPACE ENERGY CONVERSION BASE R&T

CHEMICAL ENERGY CONVERSION

TECHNOLOGY NEEDS

- THE CHEMICAL ENERGY CONVERSION AND STORAGE TECHNOLOGY PROGRAM WILL SUPPORT EMERGING PLANETARY AND SCIENCE MISSIONS DEMANDING HIGH SPECIFIC ENERGY (3X STATE OF THE ART) AND LONG-LIFE RECHARGEABLE BATTERIES, INCLUDING
    - PLANETARY SPACECRAFT
        - RECHARGEABLE LITHIUM, NICKEL-HYDROGEN SYSTEMS OR ADVANCED
    - SURFACE EXPLORERS/ROVERS
        - RECHARGEABLE LI, NIH2, FUEL CELLS OR ADVANCED CONCEPTS
    - LUNAR/MARS SURFACE POWER
        - REGENERATIVE FUEL CELLS
    - PENETRATORS
        - RECHARGEABLE LITHIUM
    - ALL NEAR-EARTH MISSIONS (ATDRSS/EOS/SATCOMS/SSF SHUTTLE EMAs)
    - PENETRATORS

SPACE ENERGY CONVERSION BASE R&T

THERMAL ENERGY CONVERSION

TECHNOLOGY NEEDS

- THE THERMAL ENERGY CONVERSION PROGRAM WILL PROVIDE THE ENHANCING AND ENABLING TECHNOLOGIES FOR:
  - SPACE STATION
    - LIGHT-WEIGHT, LOWER COST, HIGH PERFORMANCE SOLAR DYNAMIC
  - SURFACE EXPLORERS/ROVERS
    - RADIOISOTOPE THERMOELECTRIC GENERATORS OR AMTEC
  - LUNAR SURFACE POWER
    - LUNAR MATERIAL FOR THERMAL ENERGY STORAGE
  - PROBES AND PENETRATORS
    - RTGs and AMTEC
  - DEEP SPACE ORBITAL AND FLYBY MISSIONS (INCLUDING ELECTRIC PROPULSION)
    - RTGs, AMTEC, and REACTORS

SPACE ENERGY CONVERSION BASE R&T

POWER MANAGEMENT

TECHNOLOGY NEEDS

- THE POWER MANAGEMENT TECHNOLOGY PROGRAM WILL SUPPORT TECHNOLOGIES FOR CONDITIONING, DISTRIBUTION AND CONTROL OF ELECTRICAL POWER FOR THE FULL RANGE OF SPACE AND PLANETARY MISSIONS, INCLUDING:
  - EARTH OBSERVING SYSTEMS
    - INCREASED POWER DENSITY
  - SURFACE EXPLORERS/ROVERS
    - REDUCED VOLUME/SMART PMAD/LASER POWER BEAMING
  - LUNAR/MARS SURFACE POWER
    - AUTONOMOUS OPERATION OF COMPLEX SYSTEM IN HOSTILE ENVIRONMENT/LASER POWER BEAMING
  - PROBES AND PENETRATORS
    - REDUCED VOLUME/INCREASED POWER DENSITY/HOSTILE ENVIRONME
  - DEEP SPACE ORBITAL AND FLYBY MISSIONS (INCLUDING ELECTRIC PROPULSION)
    - REDUCED VOLUME/AUTONOMOUS OPERATION/HOSTILE ENVIRONMEN

THERMAL MANAGEMENT

TECHNOLOGY NEEDS

- THE THERMAL MANAGEMENT PROGRAM WILL PROVIDE HIGHLY ADVANCED THERMAL MANAGEMENT TECHNOLOGIES TO ENABLE:
  - LOW MASS SPACE RADIATORS
    - IMPORTANT FOR ALL PLANETARY AND SPACE MISSIONS
  - RADIATOR SIZE REDUCTIONS FOR SPACE POWER ELECTRONICS
    - IMPORTANT FOR ALL SPACECRAFT AND BASES
  - THERMAL CONTROL FOR SPACECRAFT INSTRUMENTS, SENSORS, AND OTHER HEAT DISSIPATING EQUIPMENT
    - IMPORTANT FOR ALL SPACECRAFT AND BASES

SPACE ENERGY CONVERSION R&T

FOCUSED POWER PROGRAMS THAT AFFECT THE BASE

- SPACE PLATFORMS
  - PLANAR AND CONCENTRATOR ARRAYS IMMUNE TO SPACE ENVIRONMENT
  - IMPROVED BATTERY SYSTEMS (APPROACHING 150 Wh/kg)
  - INTEGRATED, HIGH-EFFICIENCY POWER MANAGEMENT & CONTROL THAT IS HIGHLY AUTONOMOUS (GOAL: 2X REDUCTION IN MASS)
  - HIGH EFFICIENCY (2X - 4X IMPROVEMENT) CONVERSION SYSTEMS FOR DEEP SPACE MISSIONS
  - INTEGRATED THERMAL MANAGEMENT/HIGH TEMPERATURE ELECTRON TO YIELD 3X REDUCTION IN SPACECRAFT BUS MASS
- EXPLORATION (SURFACE POWER/MOBILE SURFACE POWER)
  - HIGH-EFFICIENCY CONVERSION SYSTEMS (e.g., STIRLING, T/E)
  - HIGH ENERGY DENSITY STORAGE (REGEN. FUEL CELLS/BATTERIES)
  - THERMAL MANAGEMENT
  - LASER POWER BEAMING

OSO TECHNOLOGY NEEDS

OAET

HIGHEST-PRIORITY

High-Rate Communications

Optical and Millimeter Wave Radio Frequencies
(for space-to-ground and space-to-space)

Advanced Data Systems

Advanced Data Storage, Data Compression, and
Information Management Systems

Advanced Navigation Techniques

New techniques for cruise, approach,
and in-orbit navigation

Mission Operations

Artificial Intelligence, Expert Systems, Neural Networks, Increased Automation in Mission Operations, Testbeds for Advanced Software, Coordination of Distributed Software, and Automated Performance Analysis of Networking Computing Environments

LBF40304a
(JCM 6843a)

INTEGRATED TECHNOLOGY PLAN FOR THE CIVIL SPACE PROGRAM

OSF TECHNOLOGY NEEDS

OAET

HIGHEST-PRIORITY

Program Unique Requirements

Vehicle Health Management
Advanced Turbomachinery (Components/Models)
Combustion Devices
Advanced Heat Rejection Technologies
High-Efficiency Space Power Systems
Water Recovery and Management
Advanced Extravehicular Mobility Unit
Electromechanical Control Systems
Crew Training Systems
Characterization of Al-Li Alloys
Cryogen Storage, Handling & Supply
TPS for High-Temp. Applications
Robotic Systems
Orbital Debris
Guidance, Navigation & Control
Advanced Avionics Architectures

Industry Driven Technologies

Signal Transmission and Reception
Advanced Avionics Software
Video Technologies
Environ. Safe Cleaning Solvents, Refrig./Foams
Non-Destructive Evaluation

LBF40302a
(JCM 6835a)

MFPE/SEI TECHNOLOGY NEEDS

OAET

HIGHEST-PRIORITY

Category 1

Radiation Protection
EVA Systems
Nuclear Thermal Propulsion
Regenerative Life Support
Cryo. Fluid Mgt, Storage & Transfer
Micro-G Countermeasures/Art. Gravity
Aerobraking

Category 2

Auto. Rendezvous & Docking
Health Maintenance & Care
In-Space Systems Assy/Processing
Surface Systems Construction/Processing
Cryogenic Space Engines
In Situ Resource Utilization
Surface Power

Category 3

Autonomous Landing
Human Factors
Surface System Mobility & Guidance
Electric Propulsion
Sample, Acquisition, Analysis & Preserv.

LBF40303a
(JCM 6836a)

INTEGRATED TECHNOLOGY PLAN FOR THE CIVIL SPACE PROGRAM

Space Exploration Initiative Technology Needs

OAET

HIGHEST-PRIORITY

Category 1

Radiation Protection
EVA Systems
Nuclear Thermal Propulsion
Regenerative Life Support
Cryo. Fluid Mgt, Storage & Transfer
Micro-G Countermeasures/Art. Gravity
Aerobraking

Category 2

Auto. Rendezvous & Docking
Health Maintenance & Care
In-Space Systems Assy/Processing
Surface Systems Construction/Processing
Cryogenic Space Engines
In Situ Resource Utilization
Surface Power

Category 3

Autonomous Landing
Human Factors
Surface System Mobility & Guidance
Electric Propulsion
Sample, Acquisition, Analysis & Preserv.

LBF40303a
(JCM 6836a)

Office of Space Science and Applications

OAET

	NEAR-TERM NEED	MID-TERM NEED	FAR-TERM NEED
HIGHEST PRIORITY	Sub mm & μ wave Sensing	Long Life, Stable, Tunable Lasers	Structures Large/Controlled/Deployed/Ant'a
	Long Life Cryo Coolers/Cryo Shielding	Solar Probe Mercury Orbiter Thermal Protect.	Robotics
	High Energy Detectors	High Vol./Density/Rate Onboard Data Storage	Precision Inter S/C Ranging/Positioning
	Sensor Readout Electronics	Interferometer Specific Technology	50 100 Kilowatt Ion Propulsion (NEP)
	Vibration Isolation Technology		Large Filled Apertures
	Efficient/Quiet Refrigerator/Freezer		Parallel S/W Env. for Model&Data Visualization
	Extreme Upper Atmosphere Instr. Platforms		Computational Techniques
2ND HIGHEST PRIORITY	High Frame Rate/Res. Video/Data Compress	Auto Sequencing & CMD Generation	SIS 3 THz Heterodyne Receiver
	2 4 to 4 Meter 100 K Lightweight PSR	Auto S/C Monitoring & Fault Recovery	SETI Detector Technologies
	Solar Arrays/Cells	32 GHz TWT/Optical Communications	Mini Ascent Vehicle/Lander Deceleration
	Automated Biomedical Analysis	Telescience/Telepresence/Art. Intelligence	Radiation Shielding for Crews
	Radiation Hardened Parts/Detectors	Improved EVA Suit/PLSS (EMU)	SAAP/Probes/In Situ Instr's/Penetrators
	Long Life/High Energy Density Batteries	Combustion Devices	Human Artificial Gravity Systems
	Real Time Environmental Control	Plasma Wave Antenna/Thermal	X Ray Optics Technology
	Space Qualified Masers/Ion Clocks		Returned Sample Biobarrier Analysis Cap
	Fluid Diagnostics		High Resolution Spectrometer
3RD HIGHEST PRIORITY	Descent Imaging/Mini RTG/Mini Camera	Regenerative Life Support	Autonomous Rendezvous/Sample Xfer/Landing
	K Band Transponders	Thermal Control System	Non Destructive Monitoring Capability
	Ultra High Gigabit/sec. Telemetry	Non Contact Temp. Measurement	Low Drift Gyros/Trackers/Actuators
	Mini Spacecraft Subsystems	3 D Packaging for 1MB Solid State Chips	Heat Shield for 16 km/sec Earth entry
	Real Time Radiation Monitoring	Microbial Decontamination Methods	Partial G/μ G Medical Care Systems
	Solid/Liquid Interface Characterization	Animal and Plant Reproduction Aids	Dust Protection/Jupiter's Rings
	Laser Light Scattering	Special Purpose Bioreactor Simulator Syst	Non Destructive Cosmic Dust Collection
	High Temperature Mat'ls for Furnaces	Rapid Subject/Sample Delivery & Return Capability	CELSS Support Technologies
	Field Portable Gas Chromatographs		
	Adv. Furnace Technology		

LBF40301
(JCM 6834)

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SPACE PHOTOVOLTAIC ENERGY CONVERSION

PRESENTED
AT THE
ITP EXTERNAL REVIEW

McLEAN VIRGINIA
JUNE 26, 1991

DENNIS J. FLOOD
LEWIS RESEARCH CENTER

SPACE ENERGY TECHNOLOGY

SPACE ENERGY CONVERSION

OAET

PHOTOVOLTAICS

OBJECTIVES

- Programatic
  Develop and Demonstrate High Efficiency Lightweight, Long Life, Durable Photovoltaic Cell and Array Technology
- Technical
  - $\geq$300 W/kg Planar Array Technology
  - $\geq$330 W/m² Conc. Arrays
  - $\leq$ 1% Cell Degradation, 10 Years GEO
  - $\geq$1000 W/kg Flexible Blanket

SCHEDULE (Strategic Budget)

- 1992 12-panel APSA
- 1993 Conc. Array Preliminary Design
- 1994 Demonstrate Thin 20% InP Cell
- 1995 Demonstrate High-Temperature Blanket
- 1996 Demonstrate >10% CIS Flexible Blanket
- 1997 Demonstrate Blanket for 300 W/kg Array
- 1998 Demonstrate 2nd Generation APSA
- 1999 Ground Test 330 W/m^2 1 kW Concentrator Array

RESOURCES(M$)

	CURRENT	3X	STRATEGIC
● 1991	2.4	2.4	2.4
● 1992	2.3	2.3	2.3
● 1993	2.4	3.4	3,3
● 1994	2.5	5.8	4.6
● 1995	2.6	7.2	5.9
● 1996	2.7	7.5	7.2
● 1997	2.8	8.8	8.5

PARTICIPANTS

- LEWIS RESEARCH CENTER
  Advanced Cell and Blanket Technology
- JPL
  Lightweight Arrays

SPACE ENERGY TECHNOLOGY

SPACE ENERGY CONVERSION

OAET

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  $\geq$330 W/m² Conc. Arrays
  $\leq$ 1% Cell Degradation, 10 Years GEO
  $\geq$1000 W/kg Flexible Blanket

SCHEDULE (Current Budget)

- 1992 LILT Degradation Mechanism/Solution Determined
- 1993 Amorphous Silicon Radiation Damage Studies Complete
- 1994 Demonstrate Low Temp. Deposition of CIS Cells on Flexible Blanket Material
- 1995 Demonstrate >19% InP Cell on Foreign Substrate
- 1996 Fabricate APSA Thin Film Cell Flexible Blanket
- 1997 Fabricate Blanket for 300 W/kg Array

RESOURCES(M$)

	CURRENT	3X	STRATEGIC
● 1991	2.4	2.4	2.4
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PARTICIPANTS

- LEWIS RESEARCH CENTER

  Advanced Cell and Blanket Technology

- JPL

  Lightweight Arrays

SPACE SCIENCE TECHNOLOGY

PHOTOVOLTAICS

TECHNOLOGY NEEDS

- SUPPORTS A BROAD SPECTRUM OF PLANNED AND FUTURE NASA/DOD/COMMERCIAL MISSION POWER REQUIREMENTS
  - SPACE STATION
  - EOS
  - LUNAR/MARS SURFACE POWER
  - EP/ORBIT TRANSFER, INTERPLANETARY TO 8 AU
  - COMSATS
  - BRILLIANT EYES
  - ALL NEAR EARTH MISSIONS

SPACE SCIENCE TECHNOLOGY

PHOTOVOLTAICS

TECHNOLOGY CHALLENGES/APPROACH

- TECHNOLOGY DEVELOPMENT CHALLENGES:
  - EXTEND MISSION LIFE
  - REDUCE ARRAY MOMENT OF INERTIA (i.e., MASS & AREA)
  - REDUCE COST
- TECHNOLOGY DEVELOPMENT APPROACH:
  - BASE R&T ON CELLS & ARRAY CONCEPTS
  - FOCUSSED DEVELOPMENT OF HIGH EFFICIENCY, LIGHTWEIGHT, CONCENTRATOR ARRAY
  - COORDINATE PLANNING & IMPLEMENTATION WITH PROSPECTIVE USERS, (e.g., SSF, EOS, SEI, DOD, etc.)

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SPACE ENEF ' TECHNOLOGY

SPACE ENERGY CONVERSION

OAET

PHOTOVOLTAIC ENERGY CONVERSION TECHNOLOGY BENEFITS

- 3X HIGHER SPECIFIC POWER
  - +30 W/KG SOA TO > 300 W/KG ADV. PLANAR
- 10X HIGHER POWER DENSITY
  - +110 W/SQ.M TO > 330 W/SQ.M
- 20X BETTER RADIATION RESISTANCE
  - +> 20% TO < 1%, 10 yrs GEO

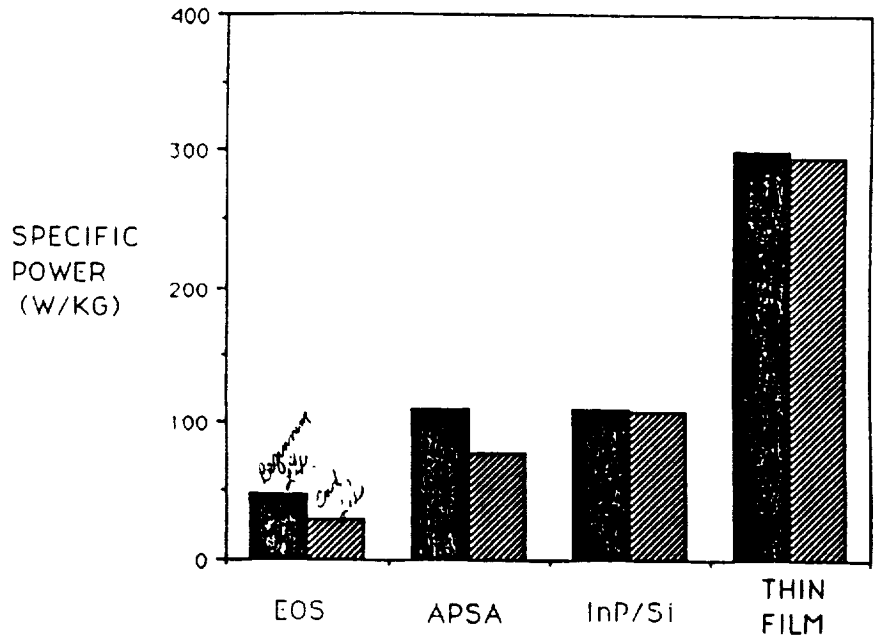
techbrft

SPACE ENEF ' TECHNOLOGY

SPACE ENERGY CONVERSION

OAET

EVOLUTION OF ARRAY SPECIFIC POWER

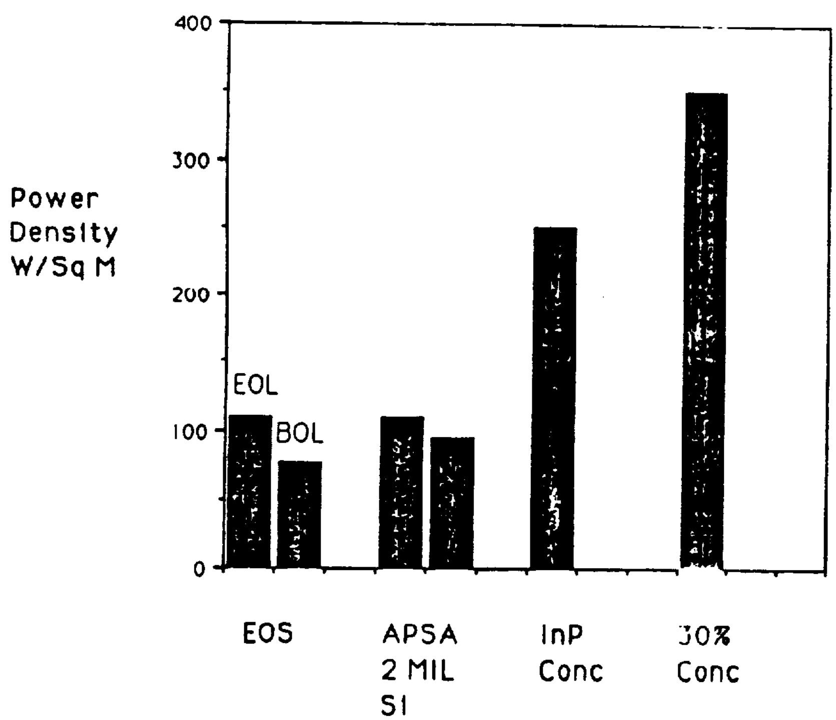


SPACE ENER' TECHNOLOGY

SPACE ENERGY CONVERSION

OAET

Evolution of Array Power Density



SPACE SCIENCE TECHNOLOGY

PHOTOVOLTAICS

STATE-OF-THE-ART ASSESSMENT

CURRENT:
- BODY MOUNTED OR DEPLOYABLE RIGID
- DEPLOYABLE FLEXIBLE ARRAYS
- NO CONCENTRATOR ARRAYS

- **Si PLANAR CELLS**
  - 110 W/m^2, 25 - 40 W/kg
  - 25% - 40% DEGRADATION, 7 YEARS GEO

    (2 mil Si CELL @ 15% DEGRADATION)
- **GaAs PLANAR CELLS**
  - $\geq$170 W/m^2, 25 - 40 W/kg
  - 15% DEGRADATION, 10 YEARS GEO
- **OAET/APSA (ADVANCED PHOTOVOLTAIC SOLAR ARRAY)**
  - 2 mil Si CELL
  - 110 W/m^2, 130 W/kg
  - 20% DEGRADATION, 10 YEARS GEO

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SPACE ENER(TECHNOLOGY

SPACE ENERGY CONVERSION

OAET

HIGH PERFORMANCE PHOTOVOLTAIC SOLAR ARRAYS

CURRENT PROGRAM

- **ADVANCED PHOTOVOLTAIC SOLAR ARRAY (APSA)**
  - COMPLETE FABRICATION AND VERIFICATION OF 12 PANEL LIGHTWEIGHT PROTOTYPE ARRAY WING
  - DEVELOP DESIGN MODIFICATIONS FOR RETRACTION AND RELATCHING
  - DEVELOP ALTERNATIVE CIRCUIT DESIGNS FOR SHADOWING AND CELL BREAKAGE
- **RADIATION EFFECTS ON LIGHTWEIGHT BLANKET COMPONENTS**
  - DETERMINE PROTON AND ELECTRON DAMAGE EQUIVALENCE FOR GaAs/Ge SOLAR CELLS
  - CALCULATE GaAs/Ge CELL BEHAVIOR FOR POTENTIAL MISSION APPLICATIONS
- **LOW INTENSITY, LOW TEMPERATURE (LILT) EFFECTS**
  - DETERMINE MECHANISM FOR LILT DEGRADATION IN SILICON
  - DETERMINE METHOD(S) FOR AVOIDING LILT DEGRADATION

APSAPROG

R&T BASE PROGRAM

HIGH PERFORMANCE PHOTOVOLTAIC SOLAR ARRAYS

PERFORMANCE OBJECTIVES

PERFORMANCE REQUIREMENT	CURRENT FLIGHT SOA	SAE	APSA	FUTURE OBJECTIVE
SPECIFIC POWER (w/kg)	30–40	65	130	300
WING POWER LEVEL (kw)	0.2–3.0	3–15	3–15	3–250
LIFETIME (years)	5–10	5–10	10–15	15–20

highperf

PHOTOVOLTAIC ENERGY CONVERSION

CURRENT PROGRAM

- PERFORMANCE VERIFICATION AND CELL FUNDAMENTALS
  - HIGH ALTITUDE AND LABORATORY SIMULATOR CELL MEASUREMENTS
  - THERMAL CYCLING
  - RADIATION DAMAGE STUDIES
- HETEROEPITAXIAL InP SOLAR CELLS
  - DEVELOP ≥ 17%, RADIATION RESISTANT InP CELL ON LOW COST, LIGHTWEIGHT SUBSTRATE
- CONCENTRATOR ARRAY TECHNOLOGY
  - DEMONSTRATE KEY COMPONENT TECHNOLOGY FOR ≥ 300 W/m² ARRAY
    - COMPLETE TESTS OF PASP-PLUS FLIGHT HARDWARE
- THIN FILM CELL R&T
  - DEMONSTRATE CIS TECHNOLOGY FOR 1000 W/kg FLEXIBLE SOLAR BLANKET
- SELECTIVE EMITTER/PV CONVERTER R&T
  - DEMONSTRATE KEY TECHNOLOGIES FOR ≥ 20% DIRECT THERMAL-TO-ELECTRIC CONVERSION
- HIGH EFFICIENCY InP CELLS
  - DEMONSTRATE ≥ 20% EFFICIENT PLANAR CELL

InP ON FOREIGN SUBSTRATE PERFORMANCE OBJECTIVES

PERFORMANCE REQUIREMENT	CURRENT SOA	DEVELOPMENT GOALS
CELL EFFICIENCY	10%	≥ 19%
DEGRADATION (10 YEARS GEO)	4%	< 1%
ARRAY SPECIFIC POWER (W/kg)		
BOL	96	380
10 YEARS GEO	92	376
ARRAY SPECIFIC AREA (W/m^2)		
BOL	82	160
10 YEARS GEO	79	158
APPROXIMATE NEED DATE		1995

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CIS BLANKET PERFORMANCE OBJECTIVE

PERFORMANCE REQUIREMENT	PRESENT SOA	DEVELOPMENT GOALS
CELL EFFICIENCY	11% * (RIGID SUBSTRATE)	≥ 11% (FLEXIBLE SUBSTRATE)
CELL DEGRADATION (10 YEARS GEO)	5% (ESTIMATED)	≤ 1%
BLANKET SPECIFIC POWER		
BOL	24 W/kg *	≥ 1000 W/kg *
10 YEARS GEO	23 W/kg *	≥ 990 W/kg *
BLANKET SPECIFIC AREA		
BOL	135 W/m^2 *	135 W/m^2 *
10 YEARS GEO	110 W/m^2 *	133 W/m^2 *
APPROXIMATE NEED DATE		1996

* ESTIMATED FROM TERRESTRIAL MEASUREMENT (NO SPACE CALIBRATED STANDARD AVAILABLE)

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SPACE ENERGY TECHNOLOGY

SPACE ENERGY CONVERSION

CONCENTRATOR ARRAY TECHNOLOGY PERFORMANCE OBJECTIVES

MINI-DOME FRESNEL LENS CONCENTRATOR ARRAY

PERFORMANCE REQUIREMENT	SOA REFLECTIVE CONCENTRATOR SYSTEMS	DEVELOPMENT GOALS MINI-DOME TECHNOLOGY
CONCENTRATOR ELEMENT EFFICIENCY	80 - 90%	> 95%
CONCENTRATOR ELEMENT MATERIAL	METALLIC REFLECTORS	POLYMERIC MATERIALS
PHOTOVOLTAIC CELL EFFICIENCY	18 - 20%	30%
ARRAY LIFETIME	10 YEARS (GEO)	10 YEARS (GEO)
COST	HIGH	LOW *
ARRAY SPECIFIC POWER (W/kg)	25 - 40	> 100
ARRAY SPECIFIC AREA (W/m2)	160 - 180	> 330
APPROXIMATE NEED DATE		1998

* TAKES ADVANTAGE OF AUTOMATED, LOW-COST FABRICATION AND ASSEMBLY TECHNIQUES

ITP91-010.7

SPACE SCIENCE TECHNOLOGY

PHOTOVOLTAICS

THIN InP SOLAR CELLS PERFORMANCE OBJECTIVE

PERFORMANCE REQUIREMENT	PRESENT SOA	DEVELOPMENT GOALS
CELL EFFICIENCY	19.1%	> 20%
CELL THICKNESS (MICROMETER)	380	10
CELL DEGRADATION 10 YEARS GEO	7.5%	<1%
BLANKET SPECIFIC POWER (W/kg)		
BOL	85	425
10 YEARS GEO	79	421
BLANKET SPECIFIC ARES (W/m2)		
BOL	173	180
10 YEARS GEO	160	178
APPROXIMATE NEED DATE		1994

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SPACE SCIENCE TECHNOLOGY
PHOTOVOLTAICS

OTHER DEVELOPMENT EFFORTS

SDIO SUPER ARRAY (SURVIVABLE)
- 15 x CONCENTRATION
- 20% GaAs CELLS
- 15 W/kg
- $\geq$ 200 W/m2

SPACE STATION FREEDOM ARRAY
- 8 x 8, 8 mil Si CELLS
- 110 W/m2
- 40 W/kg

(NO LEO RADIATION DAMAGE)

ADVANCED TDRSS ARRAY
- Si CELL TECHNOLOGY TBD
- 110 W/m2
- 35 W/kg

AIR FORCE MULTIBANDGAP CELL DEVELOPMENT
- GaAs/Ge
- GaAs/CIS
- AlGaAs/Ge
- FY91 NEW START (~ 1 $M)
- 30% GOAL
- CELL COST NOT A CONCERN

VARIOUS BLACK PROGRAMS

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SPACE ENERGY TECHNOLOGY
PHOTOVOLTAIC ENERGY CONVERSION

AUGMENTED PROGRAM

CONCENTRATOR ARRAY TECHNOLOGY

DEMONSTRATE 1 kW CONCENTRATOR ARRAY AT
> 330 W/M, 100 W/kg

THIN FILM EFFICIENCY InP CELLS

DEMONSTRATE THIN ($\leq$ 100 microns) PLANAR InP
CELLS WITH $\geq$ 20% EFFICIENCY

INITIATE PRE-PILOT PRODUCTION

ITP91-010.13

SPACE ENERGY TECHNOLOGY

PHOTOVOLTAIC ENERGY CONVERSION

ROADMAP/SCHEDULE

KEY ACTIVITIES	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000
R&T BASE										
PHOTOVOLTAIC KEY TECHNOLOGIES RESEARCH										
InP/FOREIGN SUBSTRATES	DEVELOP LOW EPD SUBSTRATE				19% CELL	RADIATION TEST				
CONCENTRATOR ARRAY	DEVELOP 30% CELL & RIGID LENS			FINAL DESIGN	COMPLETE FABRICATION		GROUND TEST			
CIS BLANKET	DEVELOP PRECURSORS		DEMO LOW TEMP. DEPOS	> 10% CELL		DEMONSTRATE BLANKET				
20% InP THIN CELL	DEMO 20% CELL	DEMO THIN CELL								

R&T BASE: PHOTOVOLTAIC ENERGY CONVERSION
SUMMARY

TECHNICAL CHALLENGE:

- SOLAR ARRAYS WITH EXTENDED LIFE, LIGHTER WEIGHT, SMALLER AREA, REDUCED MISSION COST

APPROACH:

- ADVANCED CELLS, BLANKETS, ARRAY SYSTEM COMPONENTS
- INTEGRATED ARRAY SYSTEM HARDWARE

PAYOFF:

- 10X INCREASE IN ARRAY SPECIFIC POWER
- RADIATION HARD ARRAYS
- 3X INCREASE IN POWER DENSITY

RATIONALE FOR AUGMENTATION:

- ALTERNATE/ENABLING TECHNOLOGY FOR MANY FUTURE MISSIONS
- AVAILABLE FOR NEAR, MID TERM
- RESTORES CRITICAL PARTICIPATION BY VENDORS
  - U.S. COMPETITIVE POSITION ERODING

RELATIONSHIP TO FOCUSSED ACTIVITIES AND OTHER PROGRAMS:

- JOINT ACTIVITIES, MOU's WITH A/F, SDIO, SERI, RAE

TECHNOLOGY CONTRIBUTIONS:

- OAST1 - BASELINE FOR SSF
- SILICON CELLS FOR SSF, VIRTUALLY ALL U.S. CIVIL, DOD MISSIONS
- PIONEERED GaAs CELLS - MANTECH FUNDED BY AIR FORCE

pvsumry1

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SPACE ENERGY TECHNOLOGY

SPACE ENERGY CONVERSION

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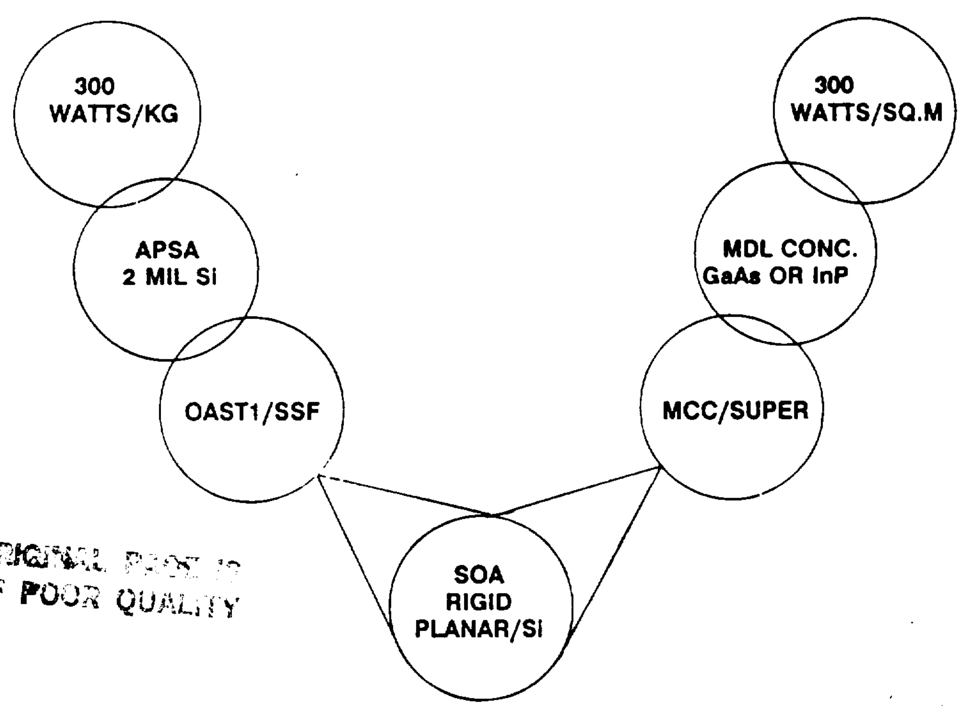
PHOTOVOLTAIC ENERGY CONVERSION

TWO DISTINCT TECHNOLOGY PATHS



TWOPATHS

SPACE ENER... / TECHNOLOGY
SPACE ENERGY CONVERSION
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PHOTOVOLTAIC ENERGY CONVERSION

o AGENCY PROGRAM HAS TWO MAJOR TECHNOLOGY SUBAREAS:

- ADVANCED ARRAY TECHNOLOGY
- ADVANCED SOLAR CELL TECHNOLOGY

o ADVANCED ARRAY TECHNOLOGY CONSISTS OF ONE MAJOR EFFORT:

- APSA AND RELATED TECHNOLOGY ISSUES
  (LILT EFFECTS, RADIATION DAMAGE, THIN CELLS, ETC)

o ADVANCED SOLAR CELL TECHNOLOGY CONSISTS OF A "MILLION PIECES"

- SINGLE CRYSTAL CELLS (InP, GaAs, AlGaAs, InGaAs, MBG's, ETC); THIN FILM CELLS (CIS, a-Si) FLEXIBLE SUBSTRATES, ALTERNATE SINGLE CRYSTAL SUBSTRATES; CONCENTRATOR CELLS & OPTICS; THERMAL CYCLING TESTS; FLIGHT TESTS (UOSAT, PASP-PLUS, APEX); CELL MEASUREMENT AND CALIBRATION, ETC, ETC

PROGRAT1

SPACE ENER... / TECHNOLOGY
SPACE ENERGY CONVERSION
OAET

PHOTOVOLTAIC ENERGY CONVERSION

o EVEN THE SOA HAS

- FEW ARRAY DESIGNS
  (COSTLY, STICK WITH WHAT'S FLOWN...)
- MANY SILICON SOLAR CELL TYPES
  10 OHM-CM, 2 OHM CM, BSF, BSR, BSFR, TEXTURED, 2X4CM, 4X2CM, 2X6CM, 6X6CM, 8X8CM, BACKSIDE GRIDS, 2MIL, 8MIL, 12MIL ETC, ETC

WHY?

o BECAUSE MISSIONS FLY IN DIFFERENT ENVIRONMENTS WITH DIFFERENT PERFORMANCE REQUIREMENTS

- NO ONE SI CELL, EVEN ON THE SAME ARRAY DESIGN, GIVES OPTIMUM PERFORMANCE FOR ALL MISSIONS

o A "CATALOG" OF ADVANCED SOLAR CELLS IS SIMILARLY NEEDED TO OPTIMIZE FUTURE MISSIONS

- ADVANCED "OPTIMUM" CELLS ARE MADE FROM DIFFERENT MATERIALS, DIFFERENT CONFIGURATIONS

<u>REASON FOR ALL THIS? THE USER COMMUNITY</u>

PROGPRT1

SPACE ENERGY CONVERSION

PHOTOVOLTAIC ENERGY CONVERSION

THE BOTTOM LINE:

- BASE R&T FUNDING AT LEAST ONE-THIRD LESS (REAL DOLLARS) THAN DECADE AGO

CAUSE:

- CONSTRAINED POWER R&T BUDGET W/LARGE EFFORTS TO DEVELOP ALTERNATE TECHNOLOGIES
  - GROWTH SPACE STATION/SOLAR DYNAMICS
  - LUNAR BASE/SP-100
  - NEP NEXT?

EFFECT:

- LARGE INVESTMENTS IN ALTERNATE SYSTEMS FOR FAR TERM (BEYOND 2000) HAVE ERODED AGENCY'S ABILITY TO HAVE IMPACT ON NEAR AND MID TERM MISSIONS

CONSEQUENCE:

- REDUCED FUNDING PUSHES NEAR AND MID TERM PV TECHNOLOGY TO FAR TERM
  - VENDORS DROP OUT
  - USER COMMUNITY CAN'T WAIT
  - MISSION CAPABILITIES COMPROMISED

INTEGRATED TECHNOLOGY PLAN
FOR THE CIVIL SPACE PROGRAM

CHEMICAL ENERGY CONVERSION AND STORAGE TECHNOLOGY PROJECT SUMMARY

SPACE ENERGY CONVERSION PROGRAM AREA OF THE R&T BASE PROGRAM

June 26, 1991

P. Bankston and M. Warshay

SPACE ENERGY CONVERSION BASE R&T

CHEMICAL ENERGY CONVERSION & STORAGE

OAET

PROGRAM OVERVIEW

OBJECTIVES

- **Programmatic**
  Develop and Demonstrate Advanced Rechargeable Battery and Fuel Cell Technologies for Space Applications
- **Technical**

Specific Energy	100-200 Wh/Kg
Energy Density	150-300 Wh/l
Operational Life	10 years

SCHEDULE

- 1993 5 Ah Engineering Model $LiTiS_2$ Cell
- 1994 Deliver Bipolar Flight Battery
- 1995 Demonstrate 1000 Cycles at 50% DOD and 100 Wh/Kg For $LiTiS_2$ Cells
  Complete 100 Wh/Kg Nickel-Hydrogen Battery
- 1996 Bi-functional Catalyst Technology Developed
- 1997 Design for 150 Wh/Kg Battery

RESOURCES($M)	BASELINE	STRATEGIC
• 1991	1.8	—
• 1992	2.0	—
• 1993	2.1	2.8
• 1994	2.2	3.4
• 1995	2.3	3.9
• 1996	2.4	4.4
• 1997	2.5	5.0

PARTICIPANTS

- Lewis Research Center
  Responsibility includes advanced batteries and fuel cells
- Jet Propulsion Laboratory
  Responsibility includes advanced batteries

SPACE ENERGY CONVERSION BASE R&T

CHEMICAL ENERGY CONVERSION & STORAGE

OAET

TECHNOLOGY NEEDS

- THE CHEMICAL ENERGY CONVERSION AND STORAGE TECHNOLOGY PROGRAM WILL SUPPORT EMERGING EARTH ORBITAL, PLANETARY AND SCIENCE MISSIONS DEMANDING HIGH SPECIFIC ENERGY (3X STATE OF THE ART) AND LONG-LIFE RECHARGEABLE BATTERIES, INCLUDING
  - PLANETARY SPACECRAFT
    - RECHARGEABLE LITHIUM, NICKEL-HYDROGEN SYSTEMS OR ADVANCED CONCEPTS
  - SURFACE EXPLORERS/ROVERS
    - RECHARGEABLE LI, NiH_2, FUEL CELLS OR ADVANCED CONCEPTS
  - LUNAR/MARS SURFACE POWER
    - REGENERATIVE FUEL CELLS
  - PROBES AND PENETRATORS
    - RECHARGEABLE LITHIUM
  - ALL NEAR-EARTH MISSIONS (ATDRSS/EOS/SATCOMS/SSF/SHUTTLE/EVAs)
  - MARS AND VENUS MISSION POWER
    - LICO2 SYSTEM
  - EMA's FOR SHUTTLE
    - BI-POLAR NIH2 WITH ELECTROCHEMICAL CAPACITORS

SPACE ENERGY CONVERSION BASE R&T

CHEMICAL ENERGY CONVERSION & STORAGE

OAET

TECHNOLOGY CHALLENGES

- REDUCE BATTERY WEIGHT (2-3 TIMES LESS THAN Ni-Cd)
- REDUCE BATTERY VOLUME (2-3 TIMES)
- INCREASE OPERATIONAL LIFE (10 YEARS)
- DEVELOP A BATTERY FOR HIGH VOLTAGE, HIGH POWER, AND PULSE APPLICATIONS
- EXTEND ACTIVE STORAGE/CHARGE RETENTION (5 YEARS)
- STABLE, HIGH PERFORMANCE FUEL CELL CATALYSTS
- IDENTIFY ADVANCED CONCEPTS CAPABLE OF FURTHER ENERGY STORAGE IMPROVEMENTS BY FACTORS OF 3-5 BEYOND SOA

SPACE ENERGY CONVERSION BASE R&T

CHEMICAL ENERGY CONVERSION & STORAGE

OAET

TECHNOLOGY BENEFITS

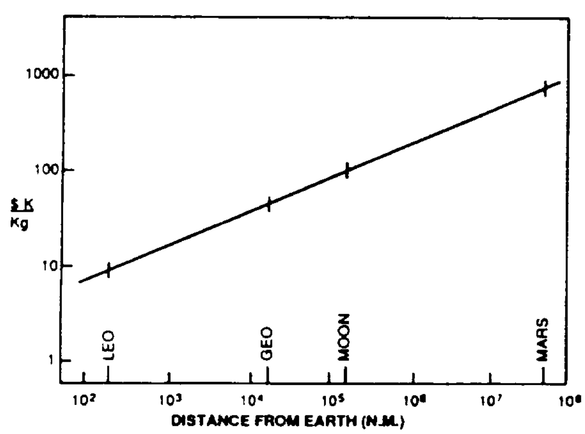
- MASS REDUCTION ENABLES SIGNIFICANT LAUNCH COST SAVINGS PER KILOWATT OR WATT-HOUR ENERGY STORED; AND INCREASE IN PAYLOAD CAPABILITY
- 2-3 TIMES SAVING IN ENERGY STORAGE VOLUME ENABLES REDUCTIONS IN SYSTEM ENVELOPE
- INCREASE OF OPERATION LIFE TO 10 YEARS OR MORE ENABLES PLANETARY MISSION APPLICATIONS
- HIGH POWER, HIGH VOLTAGE BATTERY DEVELOPMENT WOULD PROVIDE PRIMARY POWER OPTION FOR LARGE LUNAR/PLANETARY ROVERS
- STABLE, HIGH PERFORMANCE CATALYSTS WOULD ENABLE REGENERATIVE FUEL CELL UTILIZATION FOR WIDE RANGE OF LUNAR AND PLANETARY SURFACE POWER SYSTEMS

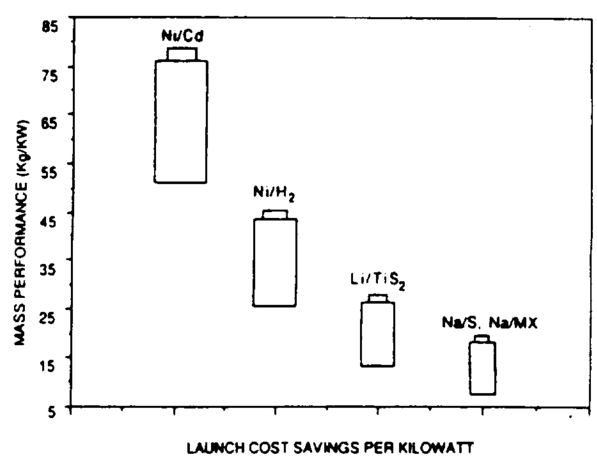
SPACE ENERGY CONVERSION BASE R&T

CHEMICAL ENERGY CONVERSION & STORAGE

OAET

MASS COST ADVANTAGE





OAET — CHEMICAL ENERGY CONVERSION & STORAGE

STATE OF THE ART ASSESSMENT

- SOA RECHARGEABLE BATTERIES ARE ACCEPTABLE, BUT POSSESS LOW SPECIFIC ENERGY (30 Wh/Kg, Ni-Cd; 55 WH/Kg, NiH_2) AND ENERGY DENSITY.
- 10 YEAR OPERATIONAL LIFE WHILE CYCLING DEMONSTRATED FOR SOME; MANY YEARS ON STAND (CRUISE) GENERALLY NOT DEMONSTRATED
- SOA RECHARGEABLE BATTERIES TYPICALLY HAVE POOR CHARGE RETENTION CHARACTERISTICS
- NO HIGH VOLTAGE, HIGH POWER SPACE BATTERY YET DEVELOPED
- STABLE, HIGH PERFORMANCE CATALYSTS ESSENTIAL TO REGENERATIVE FUEL CELL UTILIZATION IN SPACE

SPACE ENERGY CONVERSION BASE R&T

OAET — CHEMICAL ENERGY CONVERSION & STORAGE

ADVANCED RECHARGEABLE BATTERY TECHNOLOGY PERFORMANCE OBJECTIVES (CELL LEVEL)

PERFORMANCE CHARACTERISTIC	SOA BATTERIES		ADVANCED BATTERIES			
	NiCd	NiH_2	IPV NiH_2	BP* NiH_2	$LiTiS_2$	Na-S Na-MX
SPECIFIC ENERGY (Wh/Kg)	30	55	100	80	100	140-200
ENERGY DENSITY (Wh/l)	80	60	80	120	250	300
MASS PERFORMANCE (Kg/Kw)	65	35	20	25	20	14-10
CAPACITY (Ah)	5-50	30-250	30-300	30-300	5-30	100
OPERATING TEMPERATURE (°C)	-10-35	-10-35	-10-35	-10-35	0-30	350-300
CYCLE LIFE (# Cycles @ 70% DOD)	1000	40,000	40,000	40,000	1000	2000
MINIMUM LIFE TIME (Years)	10	10	10	10	5-10	5-10

* On a battery (10 cell pack) level.

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CHEMICAL ENERGY CONVERSION & STORAGE

OAET

RECENT MAJOR ACCOMPLISHMENTS

- IPV NIH2
  - 40,000 LEO CYCLES AT 80% DOD IN BOILERPLATE CELLS
  - LIGHTWEIGHT COMPONENT TECHNOLOGY DEMONSTRATED FOR 5800 CYCLES ON SUBSCALE LEVEL
  - 90% NI ELECTRODE SUBSTRATE POROSITY ACHIEVED (vs. 83% SOA)
- BIPOLAR NiH_2
  - OVER 10,000 CYCLES ACHIEVED IN ON-GOING TESTS
- $LI-TIS_2$
  - 700 CYCLES ACHIEVED AT 50% DOD IN 1 Ah CELLS
- ADVANCED RECHARGEABLE BATTERY CONCEPTS
  - CONFIRMED CYCLEABILITY OF $NaNiCl_2$ CELL; SELECTED FOR TECHNOLOGY DEVELOPMENT

SPACE ENERGY CONVERSION BASE R&T

CHEMICAL ENERGY CONVERSION & STORAGE

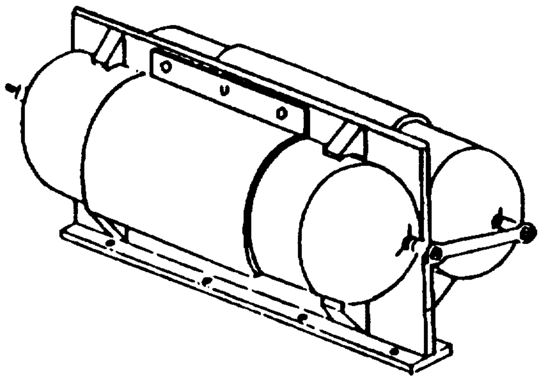
LeRC

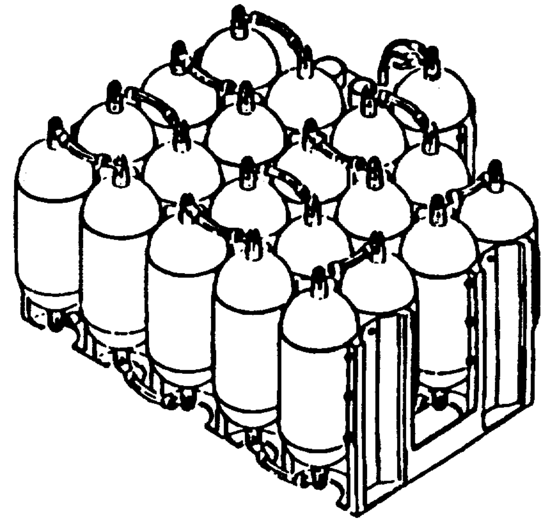
CURRENT PROGRAM

- DEVELOP GEO NICKEL HYDROGEN (NI/H_2) BATTERIES WITH INCREASED ENERGY DENSITY (100 Whr/Kg) AND RELIABILITY BY 1995
  - INTERIM 60 Whr/Kg (80% DOD) BY 1993
  - LIGHTWEIGHT COMPONENT TECHNOLOGY
  - HIGH PERFORMANCE NICKEL ELECTRODE DEVELOPMENT
- DEVELOP BIPOLAR NI/H_2 BATTERY FOR HIGH VOLTAGE, HIGH POWER, HIGH CURRENT, AND PULSE APPLICATIONS BY 1994
  - IN-HOUSE AND CONTRACT CYCLE LIFE TESTING
  - FABRICATE AND TEST ADVANCED BOILERPLATE BATTERY IN 1992
- DEVELOP ADVANCED SODIUM SULFUR (Na/S) BATTERIES AS VIABLE NASA FLIGHT SYSTEMS
  - MANAGEMENT OF $5M IN-STEP FLIGHT EXPERIMENT
  - INITIATE TECHNOLOGY DEVELOPMENT IN 1993
- DEVELOP STABLE, HIGH PERFORMANCE FUEL CELL CATALYSTS
  - COMPLETE EVALUATION OF LeRC LONG-LIFE CATALYSTS IN SOA PEM FUEL CELL IN 1993
  - CATALYST/SUPPORT TECHNOLOGY FOR REGENERATIVE FUEL CELL SYSTEM
  - BI-FUNCTIONAL CATALYST TECHNOLOGY

SIZE AND VOLUME COMPARISON OF 1.4 kWhr BIPOLAR AND IPV NICKEL HYDROGEN SYSTEMS

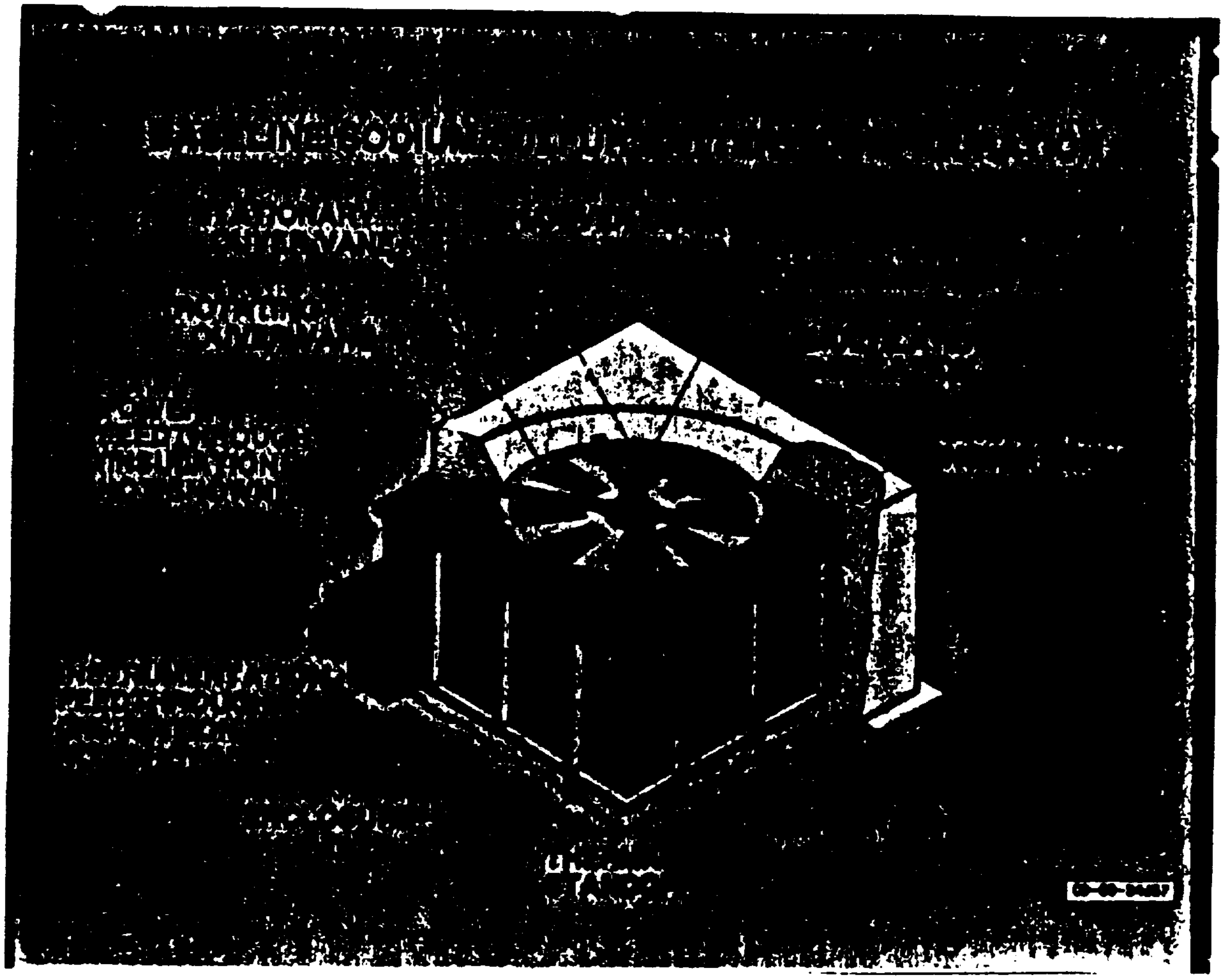
IPV BATTERY
21 CELLS (~28 VOLTS)





BIPOLAR BATTERY
2 X 100 CELLS (~133 VOLTS)

BIPOLAR DESIGN REPRESENTS
~10% VOLUME REDUCTION
COMPARED TO IPV



SPACE ENERGY CONVERSION BASE R&T

CHEMICAL ENERGY CONVERSION & STORAGE

LeRC

STRATEGIC PROGRAM

- IPV NICKEL HYDROGEN
  - DEVELOP COMMERCIAL MANUFACTURING CAPABILITY
- SODIUM SULFUR
  - ACCELERATED PROGRAM
    - TIMELY
      - BETTER PHASING
      - TIMELY PRODUCTION, MANUFACTURING CAPABILITY
- FUEL CELLS
  - CATALYST LIFE TEST, AND HALF CELL TEST

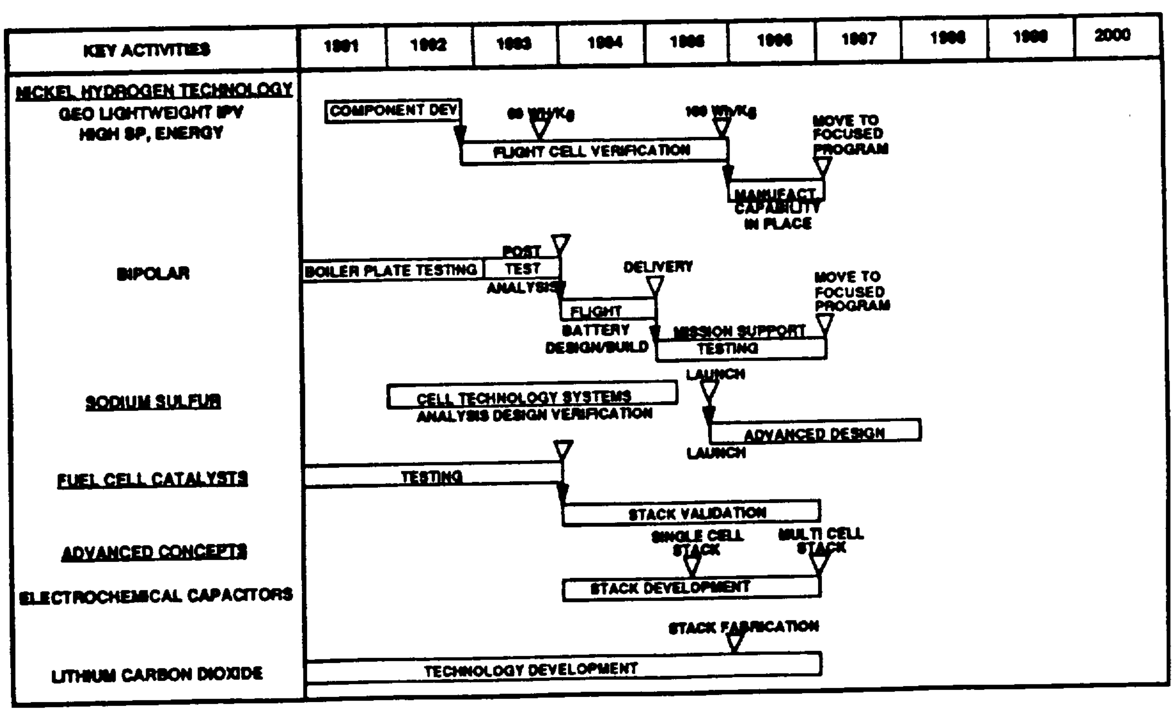
    ENHANCE IN-HOUSE FUEL CELL TESTING CAPABILITY
- ELECTROCHEMICAL CAPACITORS
  - INITIATE ELECTROCHEMICAL CAPACITOR DEVELOPMENT PROGRAM

SPACE ENERGY CONVERSION BASE R&T

CHEMICAL ENERGY CONVERSION & STORAGE

LeRC

ROADMAP/SCHEDULE



C-2

SPACE ENERGY CONVERSION BASE R&T

CHEMICAL ENERGY CONVERSION & STORAGE

JPL

CURRENT PROGRAM

- DEMO FEASIBILITY OF AMBIENT TEMPERATURE Li-TiS_2 CELL TECHNOLOGY (100 Wh/Kg) BY 1995
    - IDENTIFY STABLE ELECTROLYTES
    - EVALUATE ALTERNATE LI ANODE MATERIALS
    - DEVELOP OVERCHARGE CONCEPTS
    - DEFINE DESIGN REQUIREMENTS
    - DEVELOP 5 Ah CELLS
    - ASSESS SAFETY
- DEVELOP ADVANCED BATTERY SYSTEMS CAPABLE OF >150 Wh/Kg
    - SODIUM/METAL HALIDES
    - LITHIUM/POLYMER ELECTROLYTE/INSERTION CATHODES
        - SELECT CANDIDATE SYSTEM
        - DEMONSTRATE CYCLE LIFE
        - DEVELOP ENGINEERING MODEL CELL
        - DEMONSTRATE TECHNOLOGY

JPL

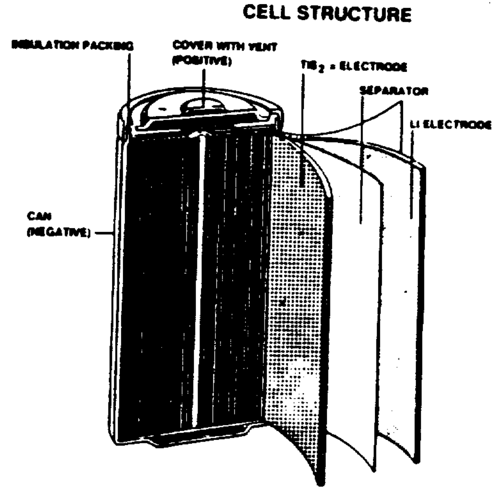
RECHARGEABLE LITHIUM CELL PROGRAM

SCALE UP OF Li-TiS_2 CELL TECHNOLOGY

CELL DESIGN

COMPONENT	150 mAh CELL	1 Ah CELL
Li ANODE	1.5 Ah (1' x 4.5" x 0.02")	6 Ah (1.6" x 10" x 0.02")
TiS_2 CATHODE	150 mAh (1' x 2" x 0.02")	1 Ah (1.6" x 8.5" x 0.02")
ELECTROLYTE	EC/2-MeTHF, 4 c.c.	EC/2-MeTHF, 6 c.c.
SEPARATOR	CELGARD 2400	CELGARD 2400
SEAL	GLASS TO METAL	GLASS TO METAL
CAN	S.S. 304L	S.S. 304L

CELL STRUCTURE



CHEMICAL ENERGY CONVERSION & STORAGE

JPL

STRATEGIC PROGRAM

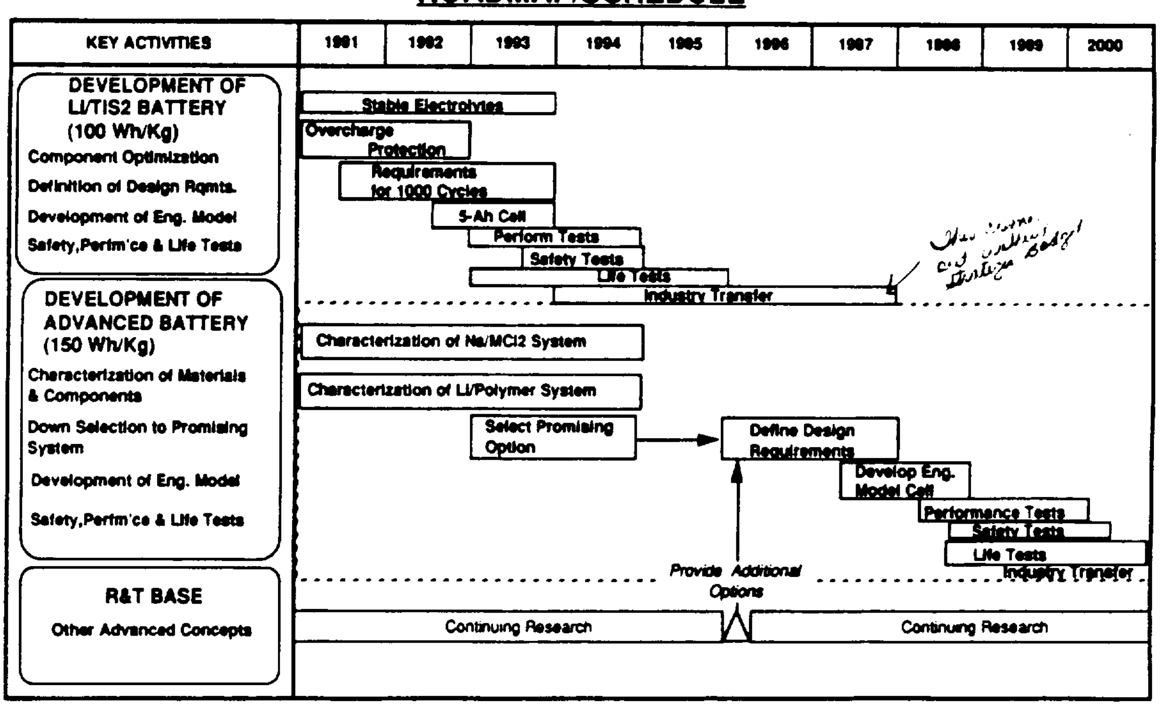
- DEVELOP AND TRANSFER TECHNOLOGY TO INDUSTRY FOR 30 Ah, 30 V, LI-TIS₂ CELL BY 1996
  - ACTIVITIES
    - ISSUE CONTRACT TO INDUSTRY
    - DEVELOP PROTOTYPE 30 Ah CELL
    - COMPLETE SAFETY, LIFE AND PERFORMANCE TESTS
- ACCELERATE 150 Whr/Kg CELL DEVELOPMENT

SPACE ENERGY CONVERSION BASE R&T

CHEMICAL ENERGY CONVERSION & STORAGE

JPL

ROADMAP/SCHEDULE



SPACE ENERGY CONVERSION BASE R&T

CHEMICAL ENERGY CONVERSION & STORAGE

OAET

RESOURCE REQUIREMENTS

FY	BASELINE FUNDING ($M)	STRATEGIC FUNDING ($M)
91	1.8	-
92	2.0	-
93	2.1	2.8
94	2.2	3.4
95	2.3	3.9
96	2.4	4.4
97	2.5	5.0

SPACE ENERGY CONVERSION BASE R&T

CHEMICAL ENERGY CONVERSION & STORAGE

OAET

RELATIONSHIP TO FOCUSSED PROGRAM

LeRC

MANAGE:

- NASA AEROSPACE FLIGHT BATTERY SYSTEMS PROGRAM - CODE Q
- EXPLORATION REGENERATIVE FUEL CELL (RFC) TECHNOLOGY DEVELOPMENT PROGRAM (SOLAR SURFACE POWER)

SUPPORT:

- EXPLORATION SOLAR SURFACE POWER PROGRAM
- SPACE STATION, HST, EOS, AND ADVANCED TDRSS NICKEL HYDROGEN BATTERY PROGRAMS

JPL

- SUPPORT NASA AEROSPACE FLIGHT BATTERY SYSTEMS PROGRAM - CODE Q
- R&T BASE TAKES LI-TIS2 BATTERY DEVELOPMENT TO "GENERIC" CELL COMPONENT AND DESIGN DEMONSTRATION
- SPACECRAFT PLATFORMS PROGRAM ADDRESSES LI-TIS2 CELL AND BATTERY DEVELOPMENT WITH APPLICATIONS FOCUS
- ADVANCED RECHARGEABLE BATTERY CONCEPTS NOT ADDRESSED IN FOCUSSED PROGRAM

CHEMICAL ENERGY CONVERSION & STORAGE

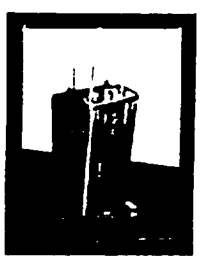
RELATED TECHNOLOGY AREAS/EFFORTS

- PRIMARY LITHIUM BATTERY DEVELOPMENT FOR CENTAUR - AIR FORCE PROGRAM MANAGED BY JPL
- LABCOM, NSWC, AND AIR FORCE ARE DEVELOPING (AMBIENT) RECHARGEABLE Li BATTERIES FOR DEFENSE APPLICATIONS - (USUALLY FOR LIMITED CYCLE LIFE - 50 CYCLES)
- DOE LABS ARE WORKING PROGRAMS TO DEVELOP Li-POLYMER AND SODIUM METAL CHLORIDE BATTERIES FOR TRANSPORTATION; ALSO Ni-METAL HYDRIDE FOR DEFENSE SPACE (JPL INVOLVED)
- AIR FORCE IS DEVELOPING Na-S BATTERY FOR DEFENSE SPACE APPLICATIONS
- SSF, HST, EOS, AND ADVANCED TDRSS Ni-H_2 BATTERY PROGRAMS SUPPORTED BY LeRC
- EMA APPLICATIONS STUDY UTILIZING BIPOLAR Ni-H_2 BATTERY
- DARPA UNMANNED UNDERSEA VEHICLE BATTERY POWER PROGRAM MANAGED BY LeRC
- DARPA UNMANNED UNDERSEA VEHICLE FUEL CELL POWER PROGRAM MANAGED BY LeRC
- LeRC COORDINATING WITH DOE PEM FUEL CELL PROGRAM (PASSENGER CAR APPLICATION)

JPL

CENTAUR Li-SOCℓ_2 BATTERY

ALLIANT VERSION



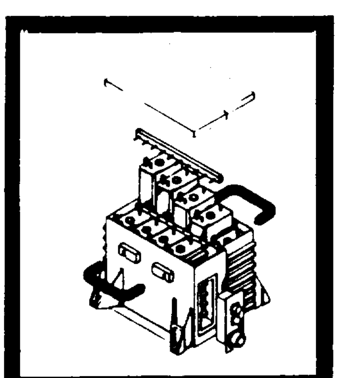
3.4 V - 250 AH CELL

FEATURES

- WEIGHT: 75 lb, 34 kg (1/2 OF EXISTING SILVER-ZINC BATTERY)
- LOW TEMPERATURE LIFE: 6 yrs @ 0°F
- AMBIENT TEMPERATURE LIFE: 1 yr @ 40-90°F (10 TIMES EXISTING SILVER-ZINC BATTERY)
- CURRENT:
  - CONTINUOUS > 40 A
  - SHORT TERM > 75 A

YARDNEY VERSION

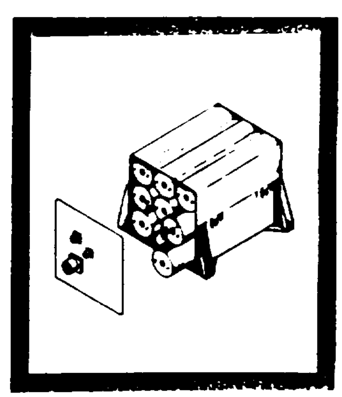
3.4 V - 250 AH CELL



28 V - 250 AH BATTERY

STATUS

QUALIFICATION OF DESIGN AND MCD 9/91



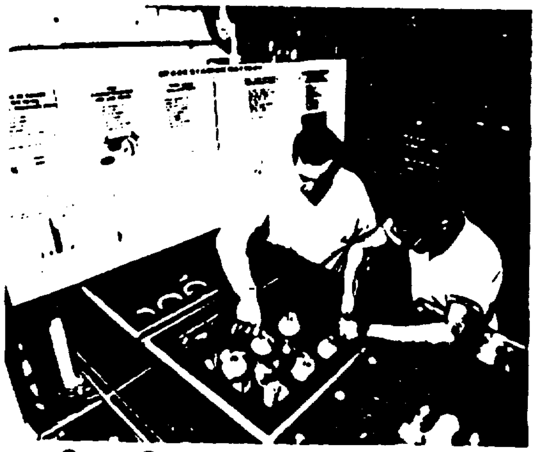
28 V - 250 AH BATTERY

NASA
C-90-10136

POWER TECHNOLOGY DIVISION

NASA
Lewis Research Center

IPV NICKEL HYDROGEN CELL TESTING
SPACE STATION FREEDOM SUPPORT



Space Station Freedom Ni-H_2 Cells

- LEO life tests 40% DOD
- 39 Flightweight cells on test
- 50 Ah and 65 Ah capacity
- 3 Commercial vendors
- 10 °C and -5 °C temperatures
- 35% Depth-of-discharge
- 26% and 31% KOH comparison
- Cell design variations

CD-90-48085

SPACE ENERGY CONVERSION BASE R&T

CHEMICAL ENERGY CONVERSION & STORAGE

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SUMMARY

- **TECHNICAL CHALLENGE:** INCREASE PAYLOAD BY REDUCING BATTERY SYSTEM WEIGHT (2X-4X) AND VOLUME WITH OPERATIONAL LIFE BEYOND 10 YEARS. ALSO, PROVIDE HIGH VOLTAGE, PULSE POWER CAPABILITY.
- **APPROACH:** DEVELOP ADVANCED NICKEL-HYDROGEN BATTERY TECHNOLOGY FOR (2X-3X) STORAGE IMPROVEMENT FOR LARGER SYSTEMS (>1kW); AND Li-TiS2 FOR 2X-3X IMPROVEMENT IN SMALLER (<1kW) SYSTEMS. DEVELOP RECHARGEABLE SODIUM SYSTEMS FOR 3X-5X IMPROVEMENTS IN LONG TERM. CONDUCT FUEL CELL CATALYST RESEARCH AND DEVELOP ADVANCED CONCEPTS.
- **PAYOFF:**
  - MASS AND VOLUME REDUCTION ENABLES SIGNIFICANT LAUNCH COST SAVINGS PER KILOWATT OR WATT-HOUR ENERGY STORED
  - INCREASE OF OPERATIONAL LIFE TO 10 YEARS OR MORE ENABLES PLANETARY MISSION APPLICATIONS
  - HIGH POWER, HIGH VOLTAGE BATTERY DEVELOPMENT WOULD PROVIDE PRIMARY POWER OPTION FOR LARGE LUNAR/PLANETARY ROVERS
  - STABLE, HIGH PERFORMANCE CATALYSTS WOULD ENABLE REGENERATIVE FUEL CELL UTILIZATION FOR WIDE RANGE OF LUNAR AND PLANETARY SURFACE POWER SYSTEMS
- **RATIONALE FOR AUGMENTATION:**
  - ACCELERATE TECHNOLOGY DEVELOPMENT FOR TIMELY TRANSFER TO USER (e.g., Na-S IN PHASE WITH FLIGHT EXPERIMENT, RFC CATALYST FOR EXPLORATION, LiTiS2 FOR PLATFORMS)
  - INITIATE NEW TECHNOLOGY DEVELOPMENT (e.g., ELECTROCHEMICAL CAPACITOR, POLYMER BATTERY)
- **RELATIONSHIP TO FOCUSED ACTIVITIES AND OTHER PROGRAMS:**
  - PROGRAM DESIGNED TO SUPPORT VIRTUALLY ALL FOCUSSED TECHNOLOGY PROGRAMS
  - LeRC AND JPL PROVIDE PROGRAM MANAGEMENT, TRANSFER TECHNOLOGY, AND COORDINATE WITH OTHER NASA CODES, DOD, AND DOE
- **TECHNOLOGY CONTRIBUTIONS:**
  - LEO IPV NICKEL HYDROGEN BATTERY TECHNOLOGY TRANSFERRED TO NASA (HST AND SSF), MILITARY AND INDUSTRY APPLICATIONS
  - LITHIUM THIONYCHLORIDE (PRIMARY) BATTERY TECHNOLOGY TRANSFERRED TO AIR FORCE FOR CENTAUR

SPACE ENERGY CONVERSION R&T

SPACE ENERGY CONVERSION R&T PROGRAM

506-41

THERMAL ENERGY CONVERSION SUBELEMENT

506-41-31

PRESENTED AT THE ITP EXTERNAL REVIEW

June 26, 1991

Power Technology Division of the Aerospace Technology Directorate
NASA Lewis Research Center

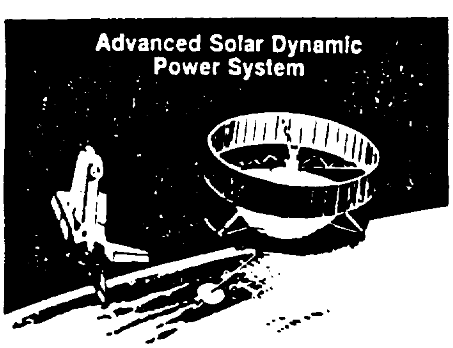
Cleveland, Ohio 44135

ITP.JEC91-001.1

SPACE ENERGY CONVERSION R&T

THERMAL ENERGY CONVERSION

WHAT WE WILL DISCUSS



- PROGRAM OVERVIEW
- MISSIONS AND BENEFITS
- CURRENT PROGRAM DESCRIPTION
- STRATEGIC PROGRAM DESCRIPTION
- ROADMAP/SCHEDULE/RESOURCES
- RELATED DEVELOPMENT EFFORTS
- SUMMARY

ITP.JEC91-001.2

SPACE ENERGY CONVERSION BASE R&T

THERMAL ENERGY CONVERSION

OAET

THERMAL ENERGY CONVERSION

OBJECTIVES

- **Programmatic**
  Develop and Demonstrate High-Efficiency Solar Dynamic, Thermoelectric, Brayton/Stirling, and Alkali Metal Thermoelectric Conversion (AMTEC) Technologies

- **Technical**
  System Efficiency - > 20%

  Specific Power - 12 W/kg (TE)
  16 - 20 W/kg (SD)
  15 W/kg (AMTEC)

SCHEDULE

- 1993 Demonstrate Technical Feasibility of Solar Dynamic Heat Receiver Technologies
- 1994 15% Efficiency, 3000-Hour AMTEC

  Complete Critical Technology Experiments to Utilize Lunar in-situ Materials for TES
- 1995 Identify Advanced Thermoelectric Material with Z = 1.4 E-03/K
- 1996 Complete Critical Technology Experiment for Advanced Sensible Heat Receiver
- 1997 Prototype Static Conversion Module Design

RESOURCES ($M)	CURRENT	STRATEGIC
• 1991	1.7	- -
• 1992	1.4	- -
• 1993	1.5	1.8
• 1994	1.6	2.1
• 1995	1.7	2.4
• 1996	1.8	2.7
• 1997	1.9	3.0

PARTICIPANTS

- **Lewis Research Center**
  Responsibility includes advanced solar dynamic systems, Brayton/Stirling technologies

- **Jet Propulsion Laboratory**
  Responsibility includes advanced thermoelectrics and AMTEC

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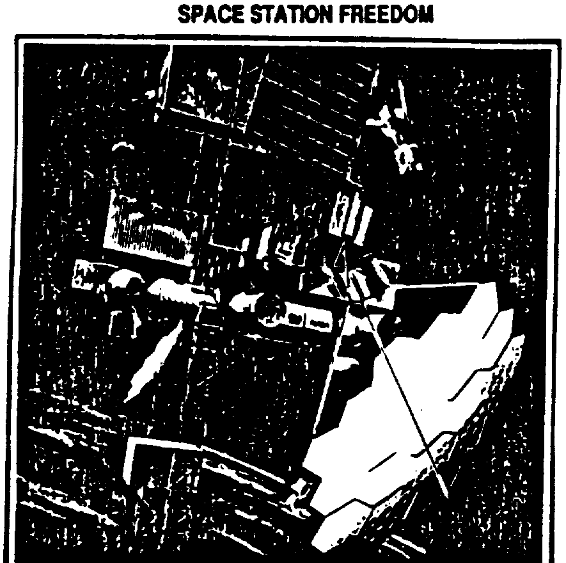
SPACE ENERGY CONVERSION R&T

THERMAL ENERGY CONVERSION

MISSION & BENEFITS
- EARTH ORBITING PLATFORMS -

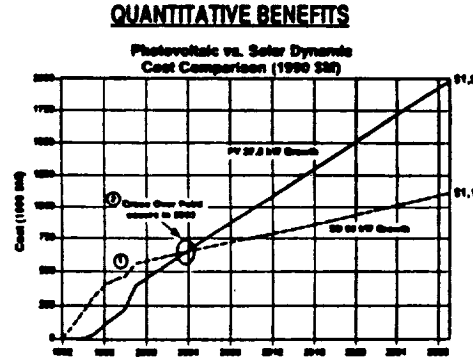
SPACE STATION FREEDOM



QUALITATIVE BENEFITS

- MORE FLEXIBILITY
- LONG LIFE COMPONENTS
- LESS DRAG
- LOWER MASS
- LOWER RECURRING COSTS
- LESS AGGREGATE EVA

QUANTITATIVE BENEFITS



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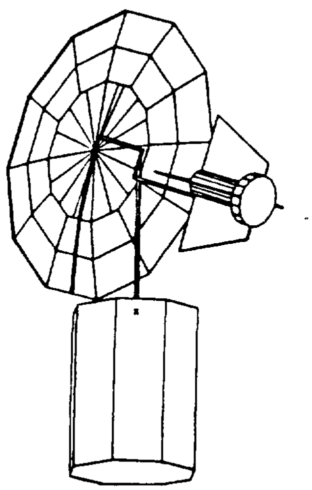
THERMAL ENERGY CONVERSION

MISSION & BENEFITS
- EARTH ORBITING PLATFORMS -

SMALL SATELLITES
COMMUNICATIONS, EARTH OBSERVING



QUALITATIVE BENEFITS

- LONGER MISSION LIFE
  - LOWER AMORTIZED COSTS
- LESS SUSCEPTIBILITY TO RADIATION EFFECTS
  - OPERATIONAL FLEXIBILITY

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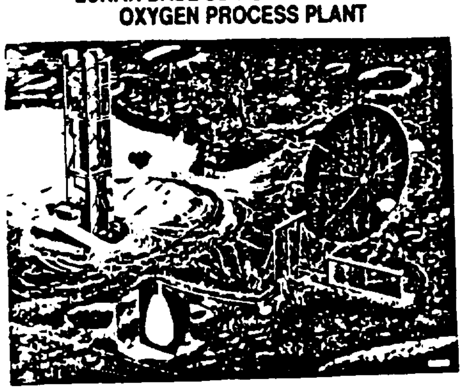
THERMAL ENERGY CONVERSION

MISSION & BENEFITS
- SURFACE POWER -

LUNAR BASE SD POWER SYSTEM & OXYGEN PROCESS PLANT

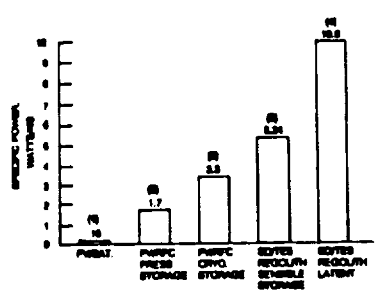


QUALITATIVE BENEFITS

- PROVIDES PROCESS HEAT PLUS ELECTRICAL POWER
- USES IN-SITU MATERIALS FOR TES
- LONG LIFE COMPONENTS

QUANTITATIVE BENEFITS

COMPARISON OF ALTERNATE SOLAR POWER SYSTEMS FOR LUNAR BASE



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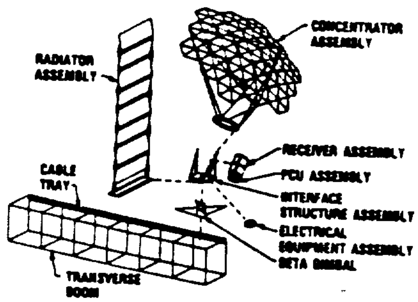
THERMAL ENERGY CONVERSION



SPACE STATION FREEDOM
SOLAR DYNAMIC POWER MODULE COMPONENTS

CURRENT PROGRAM DESCRIPTION

- IDENTIFY/ANALYZE INNOVATIVE COMPONENT/SYSTEM CONCEPTS
- DEVELOP HIGH EFFICIENCY, LOW MASS AUTO-DEPLOYABLE ADVANCED CONCENTRATOR TECHNOLOGIES
- IDENTIFY AND DEVELOP ADVANCED HEAT RECEIVER TECHNOLOGIES
- IDENTIFY AND DEVELOP THERMAL ENERGY STORAGE CONCEPTS FOR THE LUNAR SURFACE USING LUNAR REGOLITH

ITP.JEC91-00.7

THERMAL ENERGY CONVERSION

SOLAR DYNAMIC TECHNOLOGY PERFORMANCE GOALS

PERFORMANCE REQUIREMENT	CURRENT SOA	ADVANCED SOLAR DYNAMICS (ASD)
ORBITAL SYSTEMS		
• SPECIFIC POWER	5 - 8 W/kg	16 - 20 W/kg
• CONCENTRATOR		
- MASS	4 kg/sq. m.	1-2 kg/sq. m.
- ACCURACY	4 MILLIRADIANS	1 MILLIRADIAN
• RECEIVER		
- MASS	50 kg/kW	25 kg/kW
LUNAR SYSTEMS		
• SPECIFIC POWER	1 - 3 W/kg	5 - 10 W/kg

ITP.JEC91-001.8

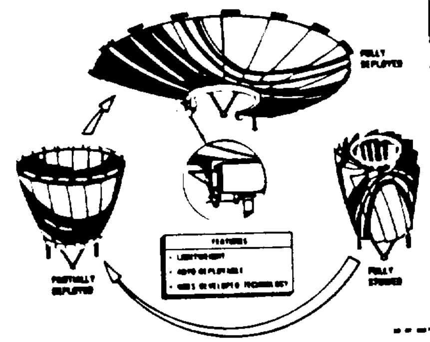
THERMAL ENERGY CONVERSION

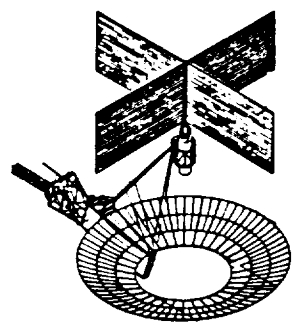
DESIGN & ANALYSES

OBJECTIVES

- IDENTIFY INNOVATIVE COMPONENT & SYSTEM CONCEPTS
  - IDENTIFY CRITICAL TECHNOLOGIES
- PROVIDE SPACECRAFT AND SUBSYSTEM INTERFACE REQUIREMENTS

NASA/CSU-AMC PROTOTYPE
AUTO-DEPLOYABLE CONCENTRATOR





ACUREX CORP. SOLAR DYNAMIC
POWER SYSTEM CONCEPT

MILESTONES

1992 COMPLETE CONCEPTUAL DESIGN OF 5 kW HYBRID (PV/SD) SPACECRAFT

1993 DEFINE SUBSYSTEM REQUIREMENTS FOR ADVANCED SENSIBLE HEAT RECEIVER

ITP.JEC91-001.9

THERMAL ENERGY CONVERSION

ADVANCED CONCENTRATORS

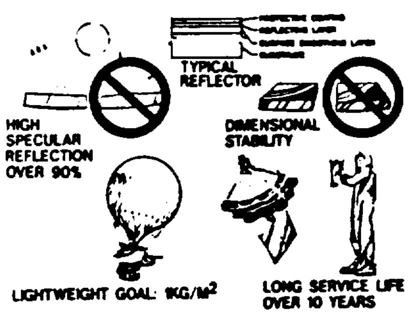
OBJECTIVES

DEVELOP FABRICATION PROCESS
TECHNOLOGY FOR:

- ACCURATE SURFACE CONTOURS (1 MILLIRADIAN)
- HIGH SPECULAR REFLECTION (90%)
- LOW SPECIFIC MASS (1-2 kg/m^2)
- HIGH CONCENTRATION RATIO (2000-5000)

HIGHLY SPECULAR ALL ALUMINUM
REFLECTOR PANEL

REFLECTOR RESEARCH OBJECTIVES



MILESTONES

1992 COMPLETE DEVELOPMENT OF ALL METAL FABRICATION TECHNIQUES

ITP.JEC91-001.10

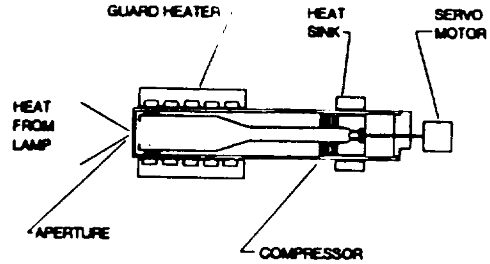
SPACE ENERGY CONVERSION R&T

THERMAL ENERGY CONVERSION

ADVANCED RECEIVERS

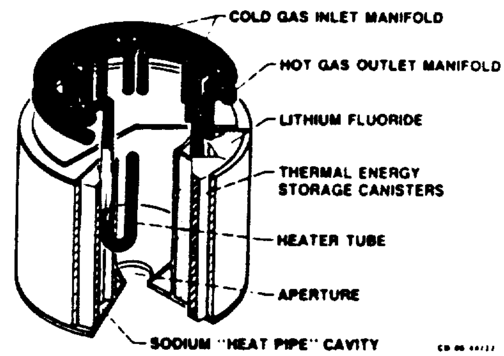
OBJECTIVES

DEVELOP HEAT RECEIVER TECHNOLOGIES THAT REDUCE THE MASS OF AVAILABLE TECHNOLOGY RECEIVERS BY AT LEAST A FACTOR OF 2



500 WATT DIRECT FLUID ABSORPTION RECEIVER EXPERIMENT

BRAYTON SOLAR RECEIVER



MILESTONES

1991 - COMPLETE INVESTIGATION OF A 0.5 kWe BENCH TOP PROTOTYPE OF DIRECT FLUID ABSORPTION RECEIVER

1993 - COMPLETE TECHNOLOGY FEASIBILITY EXPERIMENTS FOR BRAYTON CYCLE HEAT RECEIVER

1995 - COMPLETE CRITICAL TECHNOLOGY EXPERIMENTS FOR SENSIBLE HEAT RECEIVER

ITP.JEC91-001.11

SPACE ENERGY CONVERSION R&T

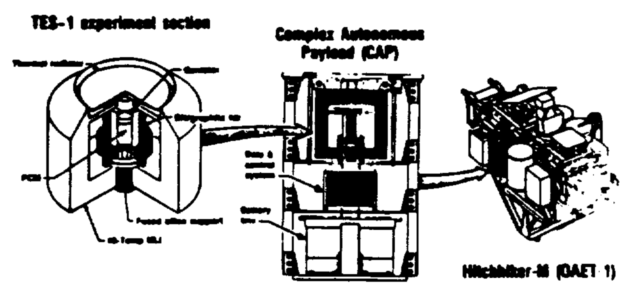
THERMAL ENERGY CONVERSION

THERMAL ENERGY STORAGE

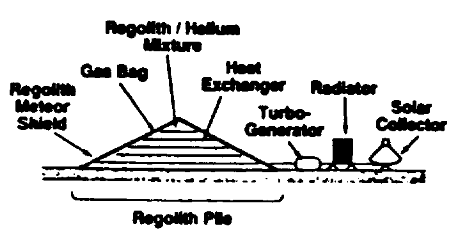
OBJECTIVES

- DEVELOP 3-D CODE FOR PREDICTING VOID FORMATION/MIGRATION IN TES MEDIA UNDER MICRO-GRAVITY CONDITIONS
- DEVELOP TECHNOLOGIES FOR UTILIZING LUNAR IN-SITU MATERIALS FOR TES

THERMAL ENERGY STORAGE TECHNOLOGY EXPERIMENT



Regolith Thermal Energy Storage



MILESTONES

1993 COMPLETE MODS TO THE NORVEX CODE TO COVER WEDGE GEOMETRY AND NON-WETTING MEDIA

1994 COMPLETE CRITICAL TECHNOLOGY EXPERIMENTS OF LUNAR TES CONCEPT

ITP.JEC91-001.12

THERMAL ENERGY CONVERSION

MAJOR ACCOMPLISHMENTS

DESIGN & ANALYSIS

- COMPARED PV AND SD POWER SYSTEMS (7 TO 35 kW RANGE) FOR AVAILABLE, NEAR TERM, & FAR TERM TECHNOLOGIES
- IDENTIFIED ENABLING TECHNOLOGIES FOR POTENTIAL LUNAR SURFACE POWER APPLICATIONS

ADVANCED CONCENTRATORS

- SELECTED SPLINED RADIAL PANELS & HINGED PETAL DEPLOYMENT CONCEPTS
- DEVELOPED FABRICATION PROCESSES FOR ALL METAL MIRROR SECTORS
  - STRETCH-FORM PANELS
  - SPRAY & SPIN COATED SURFACE LEVELIZING LAYERS
  - MICROSHEET GLASS FORMING & BONDING

ADVANCED RECEIVERS

- DESIGNED RECEIVERS FOR BRAYTON & STIRLING CONVERSION UNITS
- COMPLETED TES CRITICAL TECHNOLOGY EXPERIMENTS
  - UNIFORM FLUX WILL PRECLUDE THERMAL RATCHETING

THERMAL ENERGY STORAGE

- GERMANIUM & BORON NITRIDE ARE VIABLE TES MATERIALS
  - NO DEGRADATION AFTER 1000 CYCLES
- COMPLETED NORVEX CODE FOR LARGE VOLUME CHANGE TES MEDIA

ITP.JEC91-001.13

THERMAL ENERGY CONVERSION

STRATEGIC PROGRAM* DESCRIPTION

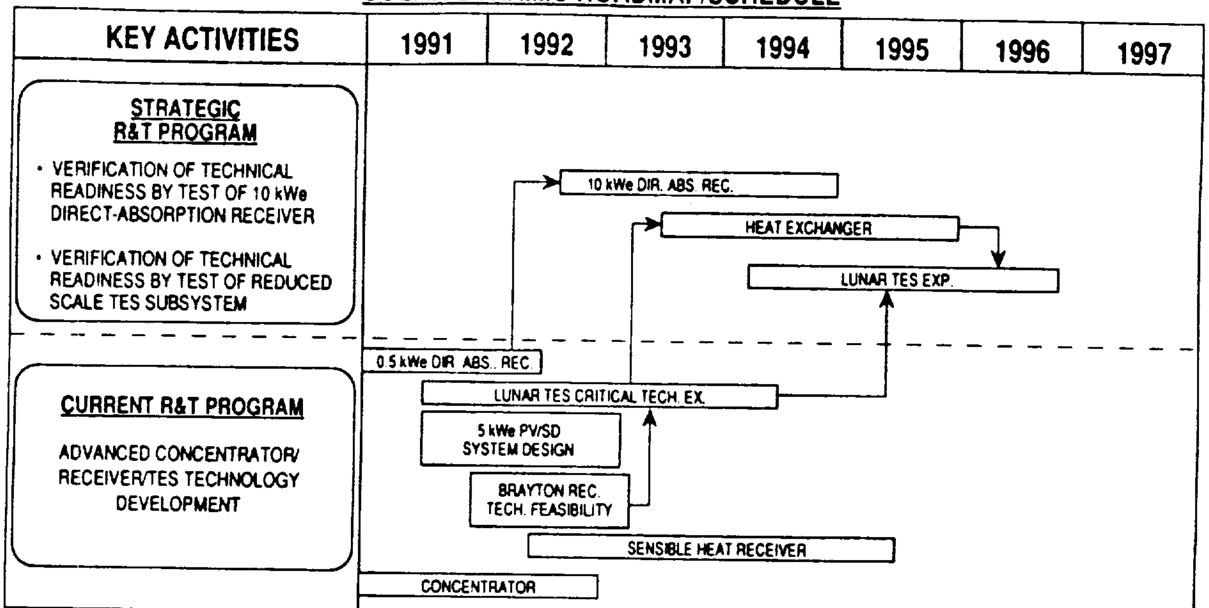
* CONTAINS ALL ELEMENTS AND ASPECTS OF CURRENT PROGRAM PLUS:

- CONDUCT EXPERIMENTS TO DEMONSTRATE TECHNOLOGY READINESS OF CRITICAL SD COMPONENTS FOR LUNAR BASE APPLICATION
  - 10 kWe DIRECT ABSORPTION RECEIVER IN SANDIA ON-SUN FACILITY
  - REDUCED SCALE TES SUBSYSTEM IN RELEVANT ENVIRONMENT

ITP.JEC91-001.14

THERMAL ENERGY CONVERSION

SOLAR DYNAMIC ROADMAP/SCHEDULE



RESOURCES ($K)	1991	1992	1993	1994	1995	1996	1997
• CURRENT	911	800	884	919	956	994	
• STRATEGIC	911	800	1000	1200	1400	1500	

ITP.JEC91-001.15

THERMAL ENERGY CONVERSION

RELATED EFFORTS

- IN-STEP TEST FLIGHT EXPERIMENTS
- CSTI HIGH CAPACITY POWER PROJECT
- DOD/AF SPACE POWER PROGRAMS
- DOE TERRESTRIAL SOLAR POWER PROGRAM

ITP.JEC91-001.16

SUMMARY

- **TECHNICAL CHALLENGE:**

  DEVELOP HIGH EFFICIENCY, STATIC THERMAL-TO-ELECTRIC CONVERSION TECHNOLOGIES TO REDUCE THE MASS AND FUEL INVENTORY IN RADIOISOTOPE BASED SPACE POWER SYSTEMS. IMPROVE THE EFFICIENCY, RELIABILITY AND LIFE, AND REDUCE THE MASS OF SPACE SOLAR DYNAMIC POWER SYSTEMS.

- **APPROACH:**

  DEVELOP ADVANCED THERMOELECTRIC MATERIALS, AND AMTEC, FOR STATIC, RADIOISOTOPE-BASED POWER SYSTEMS. INVESTIGATE OTHER STATIC CONVERSION CONCEPTS AS WARRANTED. FOR SOLAR DYNAMIC SYSTEMS, FOCUS ON FABRICATION PROCESSES FOR CONCENTRATORS, HEAT PIPE RECEIVER CONCEPTS, AND UTILIZATION OF IN-SITU MATERIALS FOR TES.

- **PAYOFF:**

  HIGH EFFICIENCY STATIC CONVERSION COULD REDUCE RADIOISOTOPE FUEL INVENTORY BY FACTORS OF 2-5, THUS SIGNIFICANTLY REDUCING FUEL COSTS, AND REDUCING MASS AND VOLUME. FOR SOLAR DYNAMIC, REDUCED ORBITAL SYSTEM MASS BY 50% AND TRANSPORTED LUNAR MASS BY FACTORS OF 2-5 ARE THE PAYOFFS.

- **RATIONALE FOR AUGMENTATION:**

  ENABLES TRANSFER OF STATIC CONVERSION TECHNOLOGY INDUSTRY. EXPANDS CURRENT SOLAR DYNAMIC PROGRAM TO INCLUDE VERIFICATION OF LUNAR BASE RECEIVER, LUNAR BASE TECHNOLOGIES.

- **TECHNOLOGY CONTRIBUTIONS:**

  THERMOELECTRIC MATERIALS MODELING CAPABILITIES UTILIZED IN HIGH CAPACITY POWER/SP-100 PROGRAMS. ALL-METAL SOLAR CONCENTRATOR TECHNOLOGIES INCORPORATED BY SSF PROGRAM IN FY'90.

ITP.JEC91-001.17

INTEGRATED TECHNOLOGY PLAN
FOR THE CIVIL SPACE PROGRAM

SPACE ENERGY CONVERSION R&T PROGRAM

POWER MANAGEMENT

JUNE, 1991

Office of Aeronautics, Exploration and Technology
National Aeronautics and Space Administration

Washington, D. C.

RWB-91Q.04.1

BASE R&T: SPACE ENERGY CONVERSION **POWER MANAGEMENT**

OBJECTIVES

- PROGRAMMATIC
  - DEVELOP AND DEMONSTRATE RELIABLE, LIGHTWEIGHT,EFFICIENT COMPONENTS AND SYSTEMS FOR THE MANAGEMENT AND DISTRIBUTION OF ELECTRICAL POWER FOR A BROAD SPECTRUM OF SPACE SYSTEMS
- TECHNICAL
  - UTILITY POWER FOR SPACE, EXPLORATION POWER, INTEGRATED CIRCUITS (PIC), ADVANCED POWER MATERIALS, ENVIRONMENTAL INTERACTION MODELS/GUIDELINES. HIGH TEMPERATURE POWER ELECTRONICS

SCHEDULE

- 1993 - SAMPIE SHUTTLE EXPERIMENT LAUNCH
  DEMONSTRATE 200°C BASEPLATE INVERTER
- 1994 - COMPLETE TECHNOLOGY DEMONSTRATION FACILITY
- 1995 - PROTOTYPE SMART POLE PIC
  1ST IC SYNCH. RECTIFIER PROTOTYPE
- 1996 - EPSAT BASED INTERACTIONS CODES DONE
  300°C COMPONENTS COMPLETE
  ADVANCED SYNCH. RECTIFIER PIC
- 1997 - SPACE POWER SYSTEMS DESIGN GUIDELINES
  DEMONSTRATE HIGH THERMAL CONDUCTIVITY
  GRAPHITE-FLORIDE CIRCUIT BOARD
  UTILITY POWER DEMONSTRATION

RESOURCES ($M)

• FY	BASELINE	STRATEGIC
• 1991	1.30	1.30
• 1992	1.17	1.17
• 1993	1.24	1.82
• 1994	1.30	2.08
• 1995	1.37	2.41
• 1996	1.43	2.67
• 1997	1.50	2.99

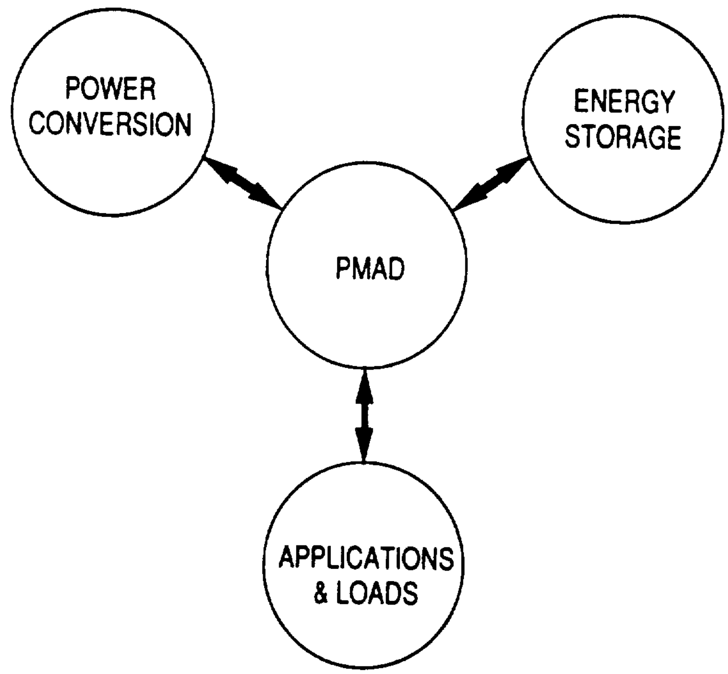
PARTICIPANTS

- LEWIS RESEARCH CENTER
  RESPONSIBILITIES: ELECTRICAL POWER MANAGEMENT
  POWER MATERIALS
  SPACE ENVIRONMENT

- JET PROPULSION LABORATORY
  RESPONSIBILITIES: POWER INTEGRATION TECHNOLOGY

POWER MANAGEMENT AND DISTRIBUTION

PERFORMS ALL POWER SYSTEM FUNCTIONS OTHER THAN GENERATION AND STORAGE



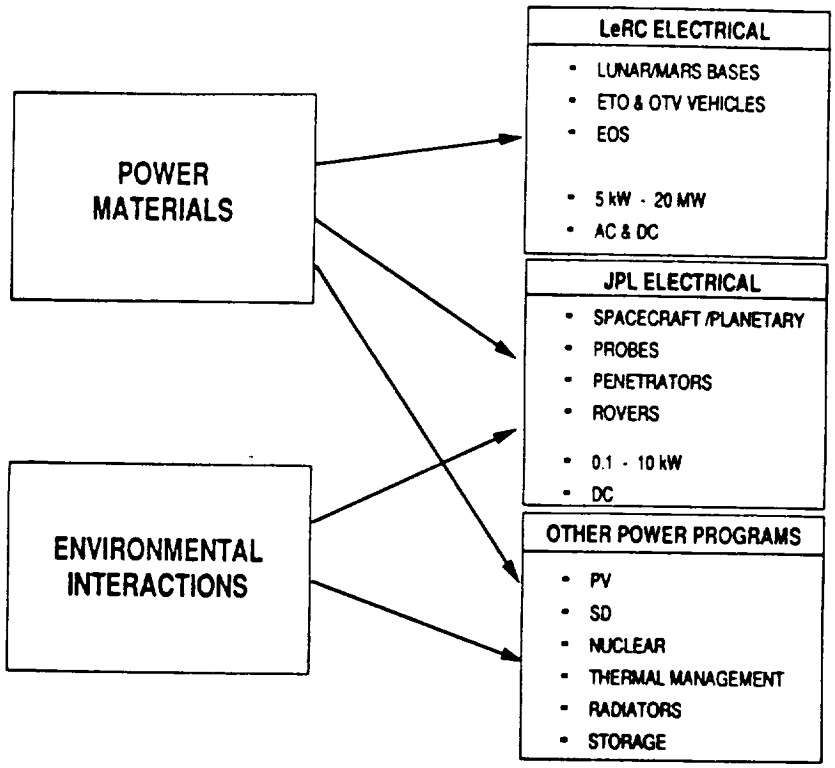
RWB-91Q.04.7

TECHNOLOGY NEEDS

- **ADVANCED POWER MANAGEMENT TECHNOLOGY FOR THE FULL RANGE OF SPACE AND PLANETARY MISSIONS, INCLUDING:**
  - **LUNAR AND MARS BASES**
    - COMPLEX, EVOLUTIONARY SYSTEMS COMPARABLE TO TERRESTRIAL UTILITIES
    - SURVIVE UNIQUE, HOSTILE ENVIRONMENTS, INCLUDING HIGH TEMPERATURES & CHARGED DUST, CORROSIVE ATMOSPHERE & GEOTAIL
    - AUTONOMOUS OPERATION
  - **ADVANCED SCIENCE MISSIONS: EOS PLATFORMS, PLANETARY SPACECRAFT, ETC.**
    - RELIABLE, LIGHTWEIGHT SPACECRAFT POWER
      - REDUCED PARTS COUNT (75%)
      - REDUCED VOLUME (40%)
      - REDUCED MASS (50%)
    - EOS PLATFORMS: HIGH POWER & DURABLE PV BLANKETS
    - SOLAR PROBE AND MDO: VERY HIGH TEMPERATURE OPERATION
  - **LAUNCH AND ORBITAL TRANSFER VEHICLES**
    - REPLACEMENT OF HYDRAULICS WITH ELECTRICAL ACTUATORS
    - LIGHTWEIGHT INTEGRATED POWER SYSTEM
    - VEHICLE HEALTH MANAGEMENT
    - STS EVOLUTION
    - NUCLEAR ELECTRIC PROPULSION - LIGHTWEIGHT ELECTRICAL SUBSYSTEM
  - **ENVIRONMENTALLY COMPATIBLE POWER SYSTEM**
    - PV
    - NUCLEAR & SOLAR DYNAMIC

RWB-91Q.04.8

PROGRAM ELEMENT INTERACTIONS



RWB-91Q.04.8

BASE R&T: SPACE ENERGY CONVERSION POWER MANAGEMENT

TECHNOLOGY DEVELOPMENT CHALLENGE

POWER MANAGEMENT IS CHARACTERIZED BY:

COMPLEX ISSUES

- ELEMENT OF ALL SPACE SYSTEMS
  - DIVERSE REQUIREMENTS
- UNIQUE, HOSTILE ENVIRONMENTS
- REQUIRES MULTIPLE TECHNOLOGIES
  - MATERIALS
  - COMPONENTS
  - SYSTEM
- NEW MISSIONS

COMPLEX INFRASTRUCTURE

- BROAD R&D BASE
  - NASA
  - OTHER AGENCIES
  - INDUSTRY
  - OTHER NATIONS
- EXTENSIVE VENDOR BASE
  - SPACE
  - AERONAUTICS & MILITARY
  - COMMERCIAL
- SPACE IS MINOR MARKET

POWER MANAGEMENT MUST MAKE SIGNIFICANT IMPACT ON NASA PROGRAMS

WITH LIMITED BUDGET AND STAFFING

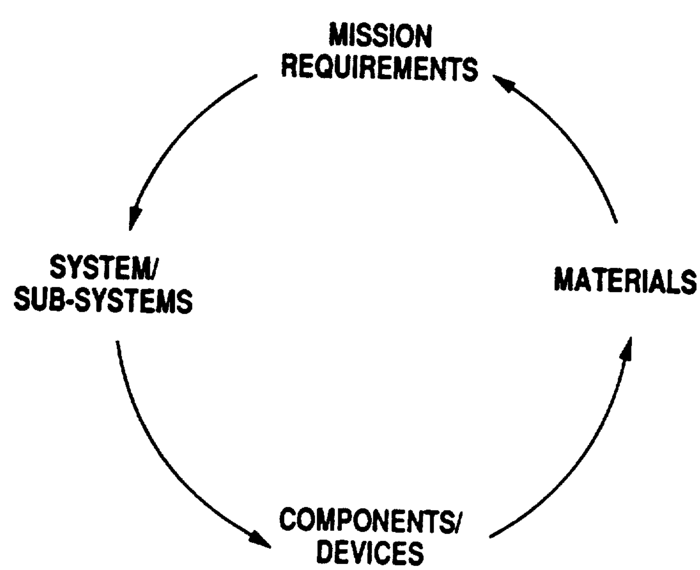
RWP-91Q.04.20

TECHNOLOGY DEVELOPMENT APPROACH

- IDENTIFY CRITICAL ISSUES AND BENEFITS THROUGH PMAD SYSTEMS ANALYSIS
- AUGMENT RESOURCES THROUGH SPECIFIC TASK ASSIGNMENTS ON RELEVANT SUBJECTS
- LEVERAGE OTHER R&D EFFORTS AND COMMERCIAL DEVELOPMENTS THROUGH SPECIFIC PROJECT EFFORTS
- MAINTAIN CLOSE COMMUNICATIONS WITH TECHNOLOGY AND USER GROUPS IN NASA, OTHER AGENCIES AND INDUSTRY

RWB-91Q.04.28

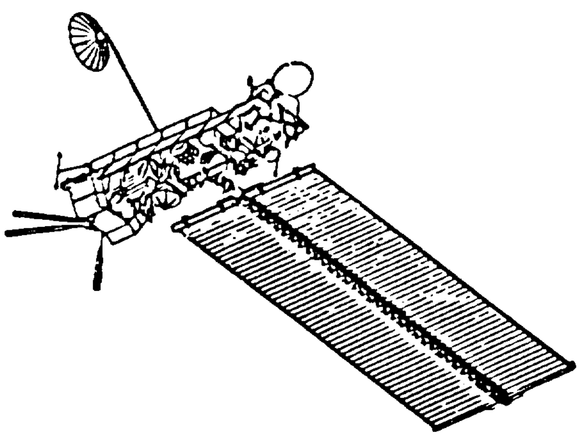
BASE R&T: SPACE ENERGY CONVERSION POWER MANAGEMENT

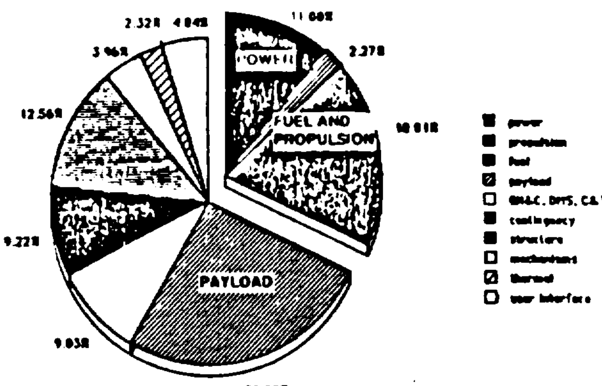


RWP 91Q.04.4

NASA **Earth Observing System** OAST

POLAR ORBITING PLATFORM WET MASS

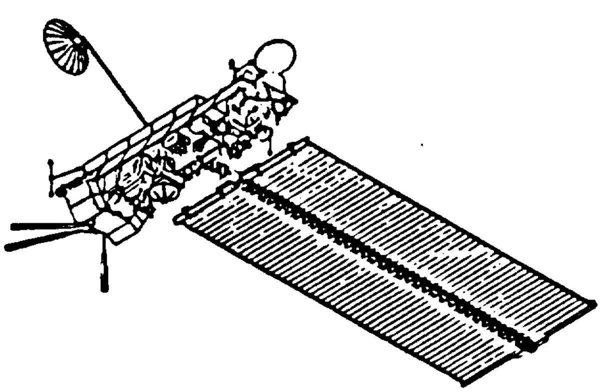


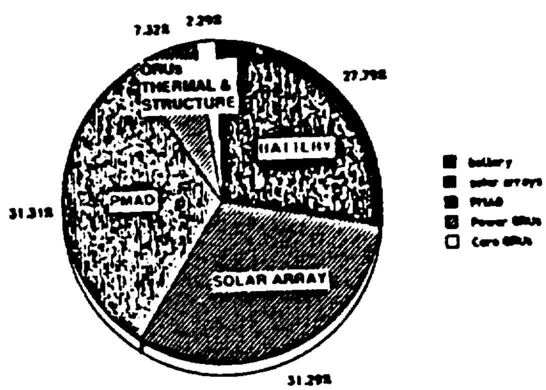


TOTAL WEIGHT IS 29715 lbs (13587 kg)

NASA **Earth Observing System** OAST

ELECTRICAL POWER SYSTEM WEIGHTS



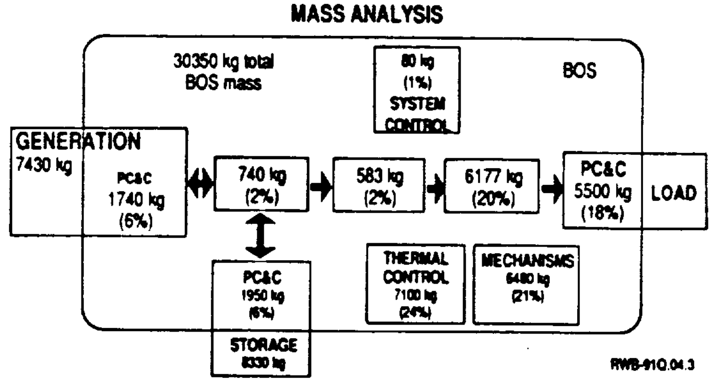


TOTAL EPS WEIGHT IS 3264.8 lbs (1484 kg)

SPACE STATION FREEDOM

- PERMANENTLY MANNED, MULTI-PURPOSE, SPACE BASED FACILITY
- POWER HALF THE COST OF SSF
  - WP - 1
  - WP - 2
  - WP - 4
- POWER CONDITIONING, CONTROL AND DISTRIBUTION (PCC&D) MASS > GENERATION & STORAGE MASS
- BALANCE OF SYSTEM IS 2/3 OF POWER SYSTEM MASS
- MAJOR DISPUTES OVER POWER DISTRIBUTION CONVENTIONS
  - HIGH VOLTAGE DC
  - 400 Hz AC
  - 20 kHz AC
  - "WILD FREQUENCY" AC
- DIFFERENT CONCEPTS
  - EXTENSION OF SPACECRAFT TECHNOLOGY
  - SPACE POWER UTILITY

MASS ANALYSIS

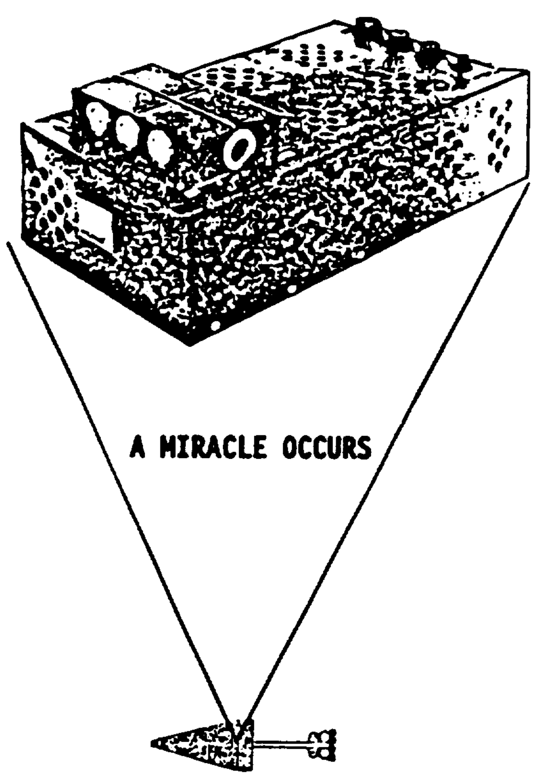


RWB-910.04.3

AEROSPACE TECHNOLOGY DIRECTORATE

POWER TECHNOLOGY DIVISION

NASA
Lewis Research Center



POWER PROCESSING,
CONTROLS, AND
DISTRIBUTION

STATE-OF-THE-ART

25-100 KG/KWE

PILOTED MARS
NEP VEHICLE

TOTAL

5-10 KG/KWE

OTHER DEVELOPMENT EFFORTS

POWER INTEGRATION TECHNOLOGY

- SOLID STATE POWER SWITCH HYBRID FOR THE CRAF AND CASSINI SPACECRAFT
  - HIGH RELIABILITY
  - 90 WATT DELIVERED TO LOAD
- SMART POLE HYBRID FOR 15 HP ELECTRICAL ACTUATOR
  - AIR FORCE PROGRAM 1988 - 1990
- SMART POLE HYBRID FOR PV POWER CONDITIONING
  - DOE FUNDED: AUGUST 1991 START

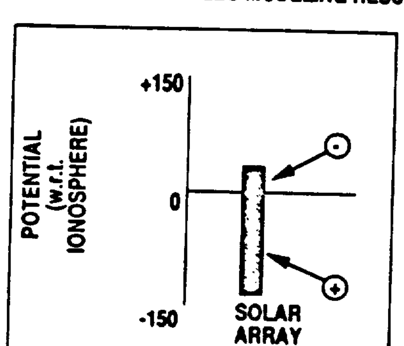
SPACE ENVIRONMENT

- EPSAT ENGINEERING CODE
  - SDIO SPONSORED
  - EMPHASIS ON MILITARY PLATFORMS
  - SURVIVABILITY KEY GOAL
  - COMPLETE IN FY 1992
- ENVIRONMENT WORKBENCH
  - EPSAT DERIVATIVE
  - SSF FUNDED, MINIMALLY
  - SPACE STATION SPECIFIC
  - COMPLETION REQUIRES LARGE INCREASE IN SSF FUNDING

RWB-91Q.04.23

PLASMA EFFECTS IDENTIFIED AS CRITICAL FOR SSF MOTIVATED ENGINEERING CHANGE

- ARRAY "FLOATS" WITH 90% OF AREA BELOW PLASMA POTENTIAL
  - SSF USES NEGATIVE GROUNDING
  - SUBJECTS MODULE SURFACES TO 140 eV IONS
  - ANODIZED AL SPUTTERS, BREAKS DOWN
- SSF ELECTRICAL GROUNDING TIGER TEAM CONVENED
  - CONFIRMED EFFECTS
  - EVALUATED GROUNDING CHANGES OR OTHER WAYS TO REDUCE SSF FLOATING POTENTIAL
  - EPSAT-BASED CODE (EWB) MADE DESIGN TRADES EASY
  - RECOMMENDED PLASMA CONTACTOR TO CONTROL POTENTIALS
  - CONSIDERING ARRAY REDESIGN TO REDUCE ELECTRON CURRENT COLLECTION - LeRC NASCAP/LEO MODELING RESULT



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OTHER DEVELOPMENT EFFORTS (con'td)

ELECTRICAL COMPONENTS AND SYSTEMS

- SYSTEMS DIAGNOSTICS, RADIATION TOLERANT SWITCHES AND HIGH TEMPERATURE MAGNETICS
  - CSTI - HIGH CAPACITY POWER
- STIRLING LINEAR ALTERNATOR - PC&C
  - CSTI - HIGH CAPACITY POWER
- NASA WIRING STUDY (KAPTON REPLACEMENT)
  - CODE - Q
- HIGH FREQUENCY LINK AND ELECTRIC ACTUATORS
  - ALS AND CODES R-M BRIDGING TECHNOLOGY
  - NLS AND SHUTTLE UPGRADES
- MORE ELECTRIC AIRPLANE
  - CODE RP & DOD
- AUTONOMOUS POWER SYSTEM & EXPERT SYSTEMS
  - CSTI - ARTIFICIAL INTELLIGENCE
- SYSTEMS ANALYSIS (SCIENCE)
  - CODE RS
- MULTI-MEGAWATT INVERTER TECHNOLOGY
  - USAF
- SPACE BASED TESTBED (SC-2000)
  - CODE C

RWB-91Q.04.24

OTHER DEVELOPMENT EFFORTS (con'td)

POWER MATERIALS

- SPACE POWER MATERIALS TECHNOLOGY
  - CODE RP
- HIGH EMITTANCE RADIATOR SURFACES FOR SP-100
  - CODE RP
- DIAMOND THIN FILMS
  - SDIO
- PV ARRAY ATOMIC OXYGEN PROTECTION
  - SSF: ARRAY PROTECTION SYSTEM ADOPTED
- PV POWER MODULE RADIATOR SURFACE LEO DURABILITY
  - SSF: RECOMMENDED MODIFICATIONS ADOPTED
- SPACE STATION FREEDOM ARRAY MATERIALS EROSION FLIGHT EXPERIMENT ON EOIM III
  - SSF
- PV ARRAY FLEXIBLE CIRCUIT CARRIER KAPTON PYROLIZATION
  - SSF

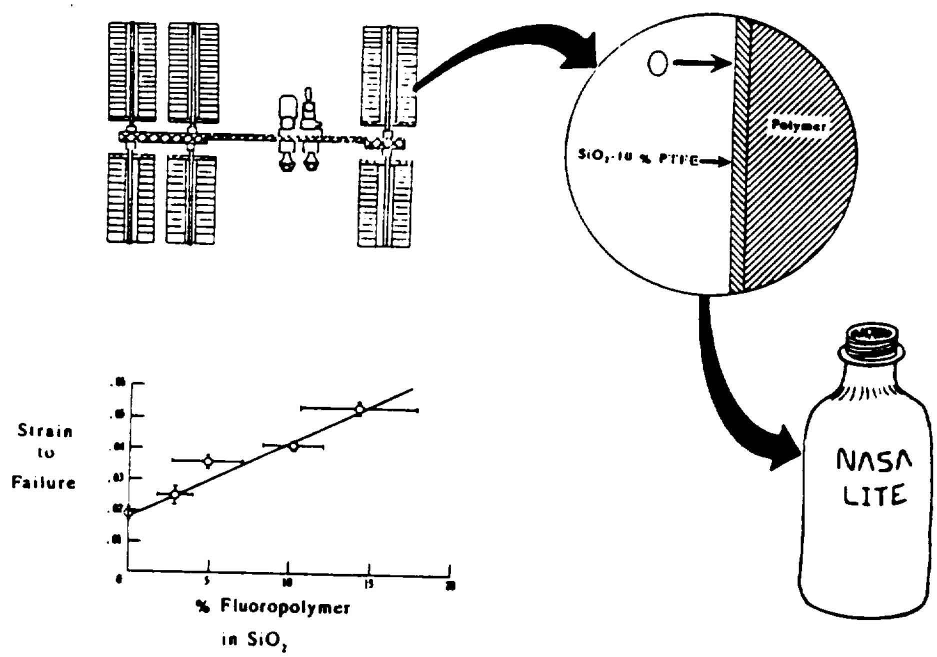
RW ~~Q.04.25~~

OTHER DEVELOPMENT EFFORTS (con'td)

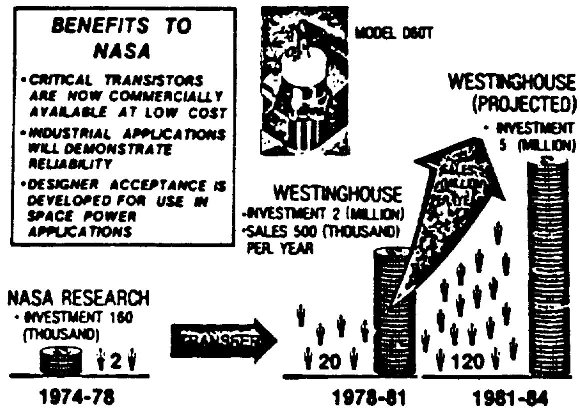
- LEO ENVIRONMENTALLY DURABLE MATERIALS
  - CODE RM
- NASA ATOMIC OXYGEN EFFECTS TEST PROGRAM
  - CODE RM
- LDEF POST RETRIEVAL ANALYSIS
  - CODE RM
- PARA-TO-ORTHO HYDROGEN CONVERSION CATALYTIC SURFACES
  - NASP
- DIAMOND-LIKE FILMS FOR OPHTHALMIC LENS PROTECTION
  - TECHNICAL UTILIZATION
- OXYGEN DIFFUSION BARRIER COATINGS FOR BEVERAGE CONTAINERS
  - EASTMAN CHEMICAL CO.

RWB-91Q.04.26

SPINOFF APPLICATIONS OF FLEXIBLE ATOMIC OXYGEN PROTECTIVE COATINGS



DEVELOPMENT OF TECHNOLOGY INFRASTRUCTURE FOR NASA MISSIONS



- NASA MINOR PLAYER IN POWER AND CONTROL ELECTRONICS INDUSTRIES
  - REQUIRED TECHNOLOGY ONLY AVAILABLE IF THERE IS AN INDUSTRIAL BASE
- OAET CAN IMPACT BASE THROUGH JUDICIOUS SEED PROJECTS
  - D60T AND OTHER POWER TRANSISTORS NOW IN WIDE USE BY NASA, DoD AND INDUSTRY
  - MCT NOW ENTERING PRODUCTION AFTER JOINT SPONSORSHIP BY NASA, DoD AND EPRI

BASE R&T: SPACE ENERGY CONVERSION **POWER MANAGEMENT**

TECHNOLOGY CHALLENGES

SPACECRAFT POWER MANAGEMENT

- ADVANCED, "CONVENTIONAL" SPACECRAFT: PLANETARY, EOS, ATDRSS, ETC.
- OBJECTIVE: EXTEND MISSION LIFE, REDUCE POWER & PROPULSION SYSTEM MASSES AND INCREASE (SCIENCE) DATA RETURN

POWER FOR ADVERSE ENVIRONMENTS

- LUNAR/MARS BASES, SELF-INDUCED ENVIRONMENTS
- OBJECTIVE: DEVELOP HIGH TEMPERATURE, RADIATION TOLERANT POWER ELECTRONICS AND RESOLVE OTHER ENVIRONMENTAL HAZARDS

UTILITY POWER

- MANNED SYSTEMS, SPACE EXPLORATION INITIATIVE
- OBJECTIVE: PROVIDE SPACE SYSTEMS WITH THE SAFETY, FLEXIBILITY, MAINTAINABILITY AND USER TRANSPARENCY NOW FOUND ONLY IN TERRESTRIAL POWER UTILITIES

RWB-910.04.21

SPACECRAFT POWER MANAGEMENT

OBJECTIVE:

EXTEND MISSION LIFE, REDUCE POWER & PROPULSION SYSTEM MASSES AND INCREASE (SCIENCE) DATA RETURN

- ADVANCED, "CONVENTIONAL" SPACECRAFT: PLANETARY, EOS, ATDRSS, ETC.

APPROACH/BENEFITS:

- POWER INTEGRATED CIRCUITS
  - REDUCE PARTS COUNT BY 75% (INCREASED RELIABILITY)
  - REDUCE WEIGHT BY 50%
  - REDUCE VOLUME BY 40%
  - INCREASED POWER DENSITY (X10) AND INCREASE EFFICIENCY
- INTERCALATED GRAPHITE ELECTRONIC ENCLOSURES
  - EQUIVALENT TO METAL BOXES FOR EMI SHIELDING AND STRENGTH
  - 1/2 - 1/4 WEIGHT OF METAL - STRUCTURES/MECHANISMS 20% OF POWER SYSTEM MASS
- EOS: ATOMIC OXYGEN PROTECTIVE COATINGS FOR SOLAR ARRAYS IN LEO
  - KAPTON SUBSTRATE MASS LOSS < 50% OVER 15 YEARS

ATD
AEROSPACE TECHNOLOGY DIRECTORATE

POWER TECHNOLOGY DIVISION

NASA
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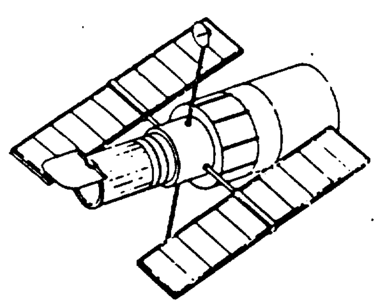
CONVENTIONAL SPACECRAFT POWER

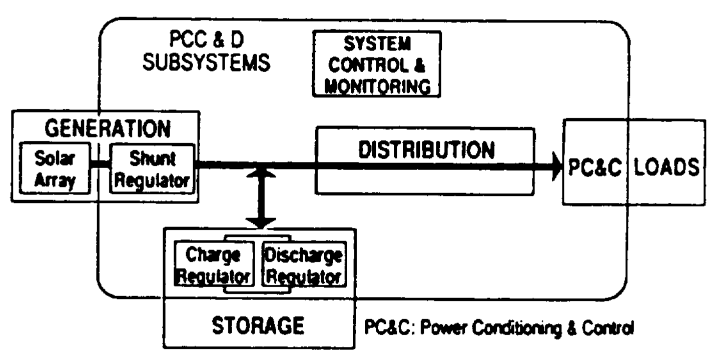


SYSTEM DRIVERS

- DEDICATION MISSION
- MINIMUM MASS
- HIGH RELIABILITY
  - MINIMAL ON-ORBIT REPAIR

MULTIPLE, INCOMPATIBLE, "STANDARD" BUSES

- GENERATION: SOLAR ARRAY OR RTG
- STORAGE: BATTERIES
- POWER CONDITIONING CONTROL AND DISTRIBUTION
  - SINGLE/DUAL BUS
  - FULL, SUNLIGHT OR UNREGULATED
  - SHUNT OR PEAK POWER TRACKER
  - 28-50 VDC



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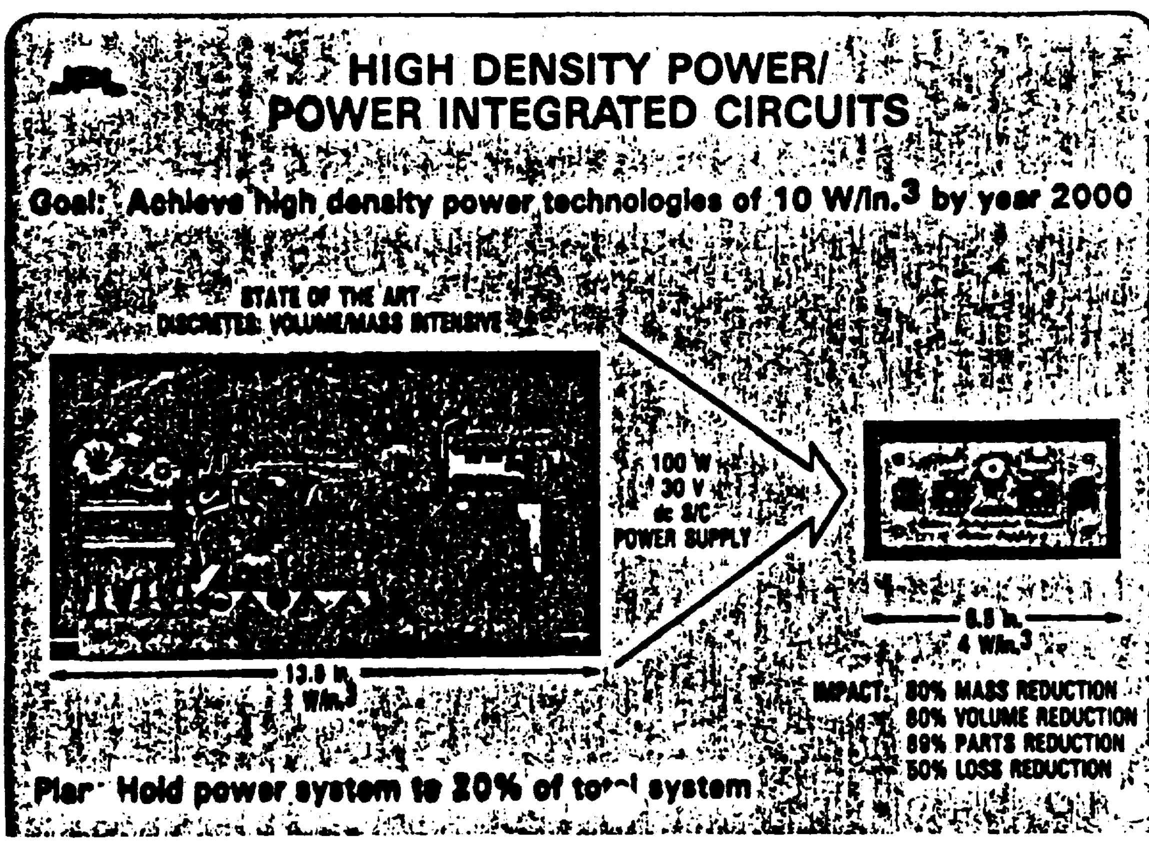
≡ OAET

POWER INTEGRATION TECHNOLOGY

STATE OF THE ART ASSESSMENT

- GENERAL ASSESSMENT: CURRENT GENERIC POWER MODULES ARE OF VERY LIMITED UTILITY (e.g. low power, simple functions), LOW AVERAGE EFFICIENCIES, WILL NOT MEET SPACE APPLICATION REQUIREMENTS.
- DETAILED ASSESSMENT:
    - CURRENT HYBRID MODULES ARE DRIVEN BY THE AUTOMOBILE INDUSTRY FIRST, PC INDUSTRY SECOND
    - CURRENT, MULTI-FUNCTION or SMART, HYBRID MODULES ARE LIMITED IN POWER DELIVERY (e.g. 30 WATTS DISSIPATION)
    - HYBRID TECHNOLOGY IS NOT READY TO SUPPORT THE THERMAL NEEDS OF A SPACE BOUND DEVICE
    - MONOLITHIC TECHNOLOGY FOR POWER INTEGRATED CIRCUITS IS LIMITED TO LOW POWER (1 TO 3 WATTS)
    - MONOLITHIC PROCESSING OF POWER INTEGRATED CIRCUITS, INTEGRATING HIGH POWER AND CONTROL FUNCTIONS, IS NOT A MATURE TECHNOLOGY

JUNE 26, 1991

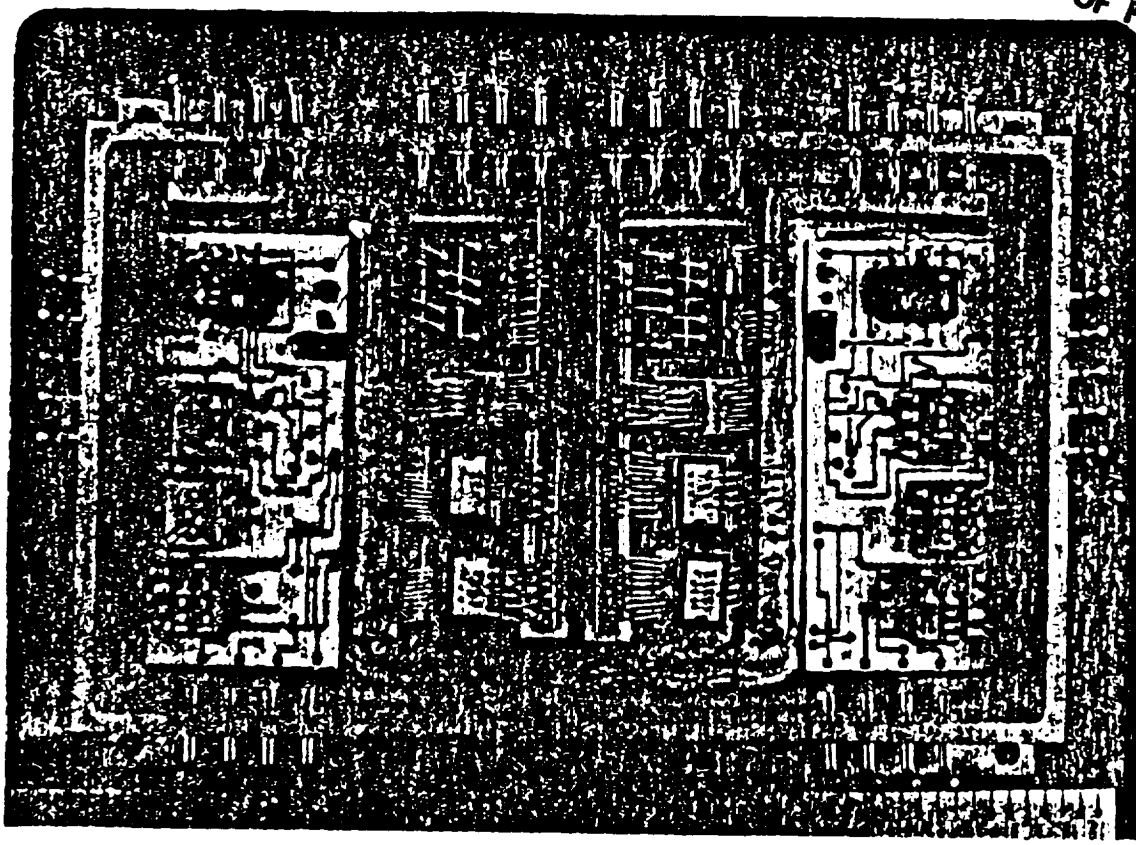


PL
...on Laboratory
Institute of Technology

PROTO HYBRID POW_R SWITCH

WESTINGHOUSE FOUNDRY 2 SWITCHES, DRIVERS AND INTERFACE ICs

ORIGINAL PAGE IS OF POOR QUALITY



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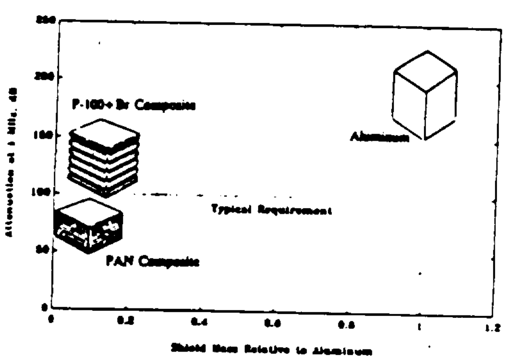
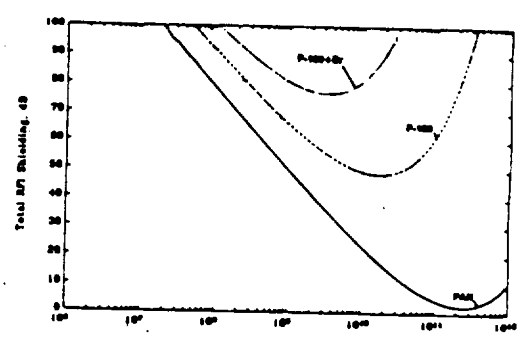
POWER TECHNOLOGY DIVISION

NASA Lewis Research Center

INTERCALATED GRAPHITE COMPOSITE EMI SHIELDS



METALLIC SHIELDING -- COMPOSITE WEIGHT

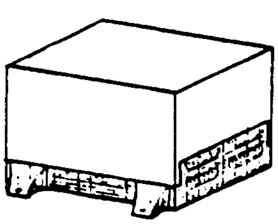


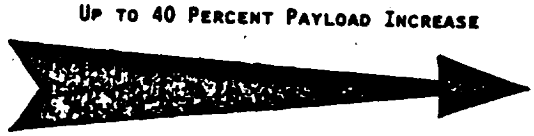
AT LEAST 80 dB SHIELDING/MM THICKNESS

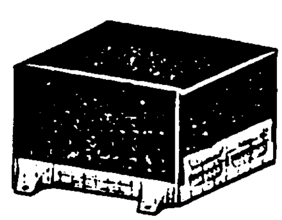
80 PERCENT REDUCTION IN SHIELD MASS

16 PERCENT REDUCTION IN POWER SYSTEM MASS

UP TO 40 PERCENT PAYLOAD INCREASE

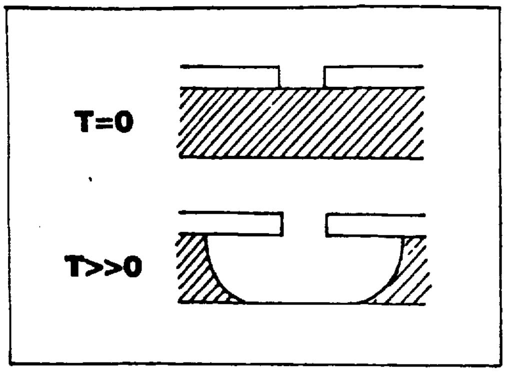


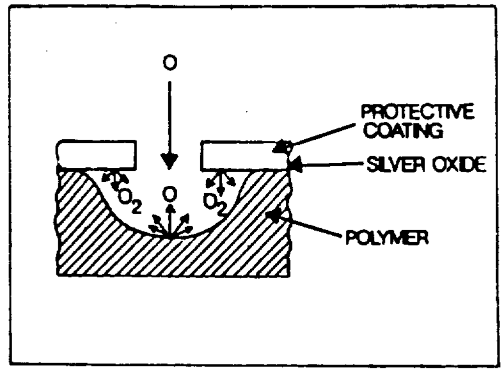




COMPARED TO STAND/ ∽, ALUMINUM EMI COVERS

ATOMIC OXYGEN PROTECTIVE COATINGS FOR LOW EARTH ORBIT POWER SYSTEM SURFACES





ATOMIC OXYGEN ATTACK

- O OCCURS AT DEFECTS IN COATING
- O RESULTS IN LARGE AREA OF DAMAGE
- O OPTICAL THEN MECHANICAL DEGRADATION

RECOMBINATIVE PROTECTIVE COATINGS

- O COATING CATALYSES 2O --> O_2 REACTION
- O LIMITS UNDERCUTTING DAMAGE

50% REDUCTION IN SOLAR ARRAY BLANKET MASS

BASE R&T: SPACE ENERGY CONVERSION   POWER MANAGEMENT

POWER FOR ADVERSE ENVIRONMENTS

OBJECTIVE:

- DEVELOP HIGH TEMPERATURE, RADIATION TOLERANT POWER ELECTRONICS AND RESOLVE OTHER ENVIRONMENTAL HAZARDS
  - LUNAR/MARS BASES
  - SELF-INDUCED ENVIRONMENTS

APPROACH/BENEFITS:

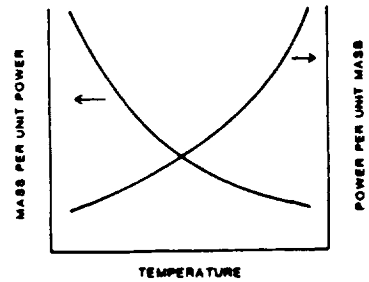
- DEVELOP RADIATION-HARD, HIGH-TEMPERATURE POWER ELECTRONICS: MATERIALS, DEVICES AND SYSTEMS
  - ALLOW OPERATION ON LUNAR SURFACE WITHOUT NEED FOR INSULATED ENCLOSURES AND HEAT PUMPS
  - REDUCE SIZE AND MASS OF LOW TEMPERATURE RADIATOR BY FACTOR OF 2 OR MORE
  - ENABLE NUCLEAR AND SD POWER SYSTEMS
- MODEL INTERACTIONS BETWEEN POWER SYSTEMS AND VARIOUS SPACE PLASMAS AND GASES
  - AVOID DISABLING ELECTRICAL DISCHARGES AND SYSTEM DEGRADATION
  - PROVIDE ENVIRONMENTAL GUIDANCE TO SYSTEM DESIGNERS
- AVOID DAMAGE AND SYSTEM DEGRADATION DUE TO LUNAR AND MARS DUST
  - WIND AND OTHER ABRASION
  - SHADOWING OF SOLAR ENERGY COLLECTIONS AND RADIATOR SURFACES

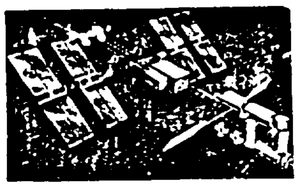
NASA
C-89-11144

HIGH TEMPERATURE ELECTRONICS PROGRAM

GOALS

- REDUCE RADIATOR WEIGHT IN SPACE SYSTEMS BY RAISING OPERATING TEMPERATURE FROM 100°C TO 300°C
- HOSTILE ENVIRONMENT TOLERANCE
- IMPROVE RELIABILITY AND LIFETIME
- HIGHER ENERGY DENSITIES
- LESS THERMAL MANAGEMENT REQUIREMENTS
- REDUCE LAUNCH COST





TECHNOLOGICAL DEVELOPMENTS

- ADVANCED MATERIALS: DIELECTRICS, INSULATION, SEMICONDUCTOR, MAGNETICS
- COMPONENTS: CAPACITORS, INDUCTORS, SWITCHES, TRANSISTORS, CABLES, TRANSFORMERS, CIRCUIT BOARDS, INVERTERS, GENERATORS, COMPUTERS

APPLICATIONS

- SPACE EXPLORATION AND DOD SYSTEMS
- SPACE NUCLEAR POWER
- ADVANCED AND CONVENTIONAL AIRCRAFT

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POWER TECHNOLOGY DIVISION

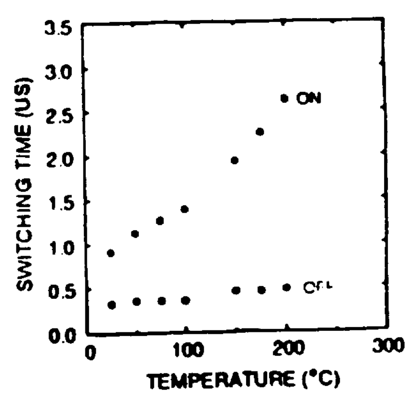
NASA
Lewis Research Center

200°C-BASEPLATE ELECTRONICS

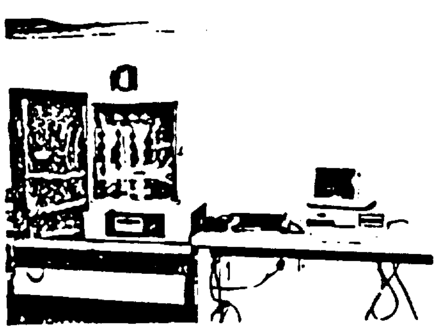
SURVIVES SEVERE ENVIRONMENTS AND LIGHTENS RADIATORS

GOAL: BUILD & TEST ASSEMBLY

- ACHIEVABLE (100°C > SOA)
- UNCOVERS MISSING TECHNOLOGY
- EXCEEDS LUNAR TEMPERATURE (130°C)
- REDUCES RADIATOR AREA > 2
- BROAD SPINOFFS



MCT SWITCHING TIMES

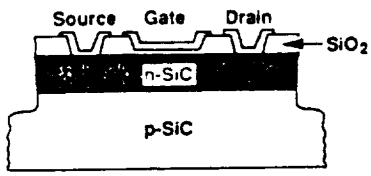


H. T. TEST LAB

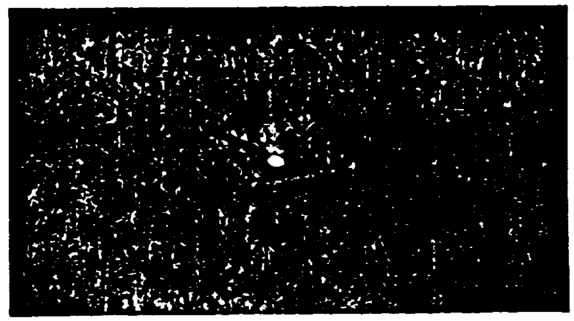
- SUNY/AUBURN GRANTS INITIATED
- COMPONENTS TESTED
  - MCT
  - CAPACITORS
  - INSULATION
- LABS SET UP
- CUSTOM COMPONENTS ORDERED

SILICON CARBIDE TECHNOLOGY FOR HIGH TEMPERATURE ELECTRONIC SWITCHES

Goal:
Develop and demonstrate a high temperature and radiation resistant SiC MOSFET power switch



SiC MOSFET Structure



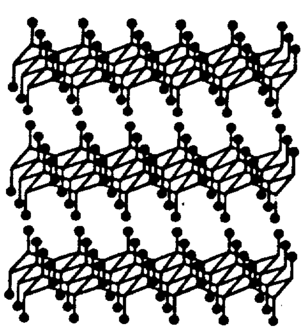
Recently fabricated 6H-SiC grown junction light emitting diode operating at 600 °C

Accomplishments
- Demonstrated high quality 6H-SiC epitaxial film growth processes
- Demonstrated capability to dope 6H-SiC films p-type with aluminum
- Fabricated prototype 6H-SiC MOSFET and successfully tested to 500 °C

CD-90-48911

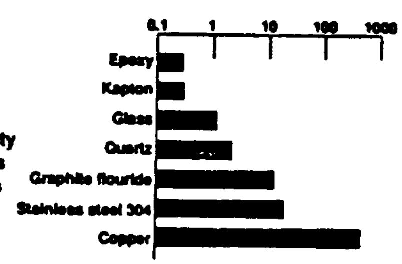
GRAPHITE FLOURIDE HIGH THERMAL CONDUCTIVITY PRINTED CIRCUIT BOARDS

	Graphite fiber (P-100)	Graphite fluoride (CF[illegible])	Fiber glass (S Glass)
Electrical resistivity (Ω cm)	2.5×10^{-4}	10^{11}	10^{14}
Thermal conductivity (W/m-K)	300	11	1.1
Young modulus (Msi)	105	25	12
Longitudinal tensile Strength (Ksi)	300	40	500
Coefficient of thermal expansion (CTE) (ppm/K)	-1	8	3
Density (g/cm^3)	2.18	2.5	2.5



Molecular structure of graphite flouride (CF)n

Thermal conductivity of various materials



CD-90-48734

CVD DIAMOND FILMS FOR HIGH POWER ELECTRONICS

SYNTHESIS

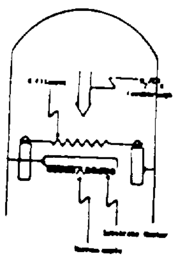
CHARACTERIZATION

& MODELLING

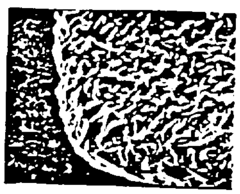
OF CVD DIAMOND

WILL ENABLE:

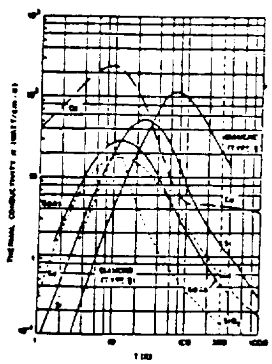
HFCVD

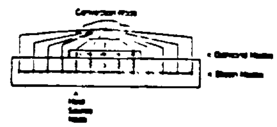


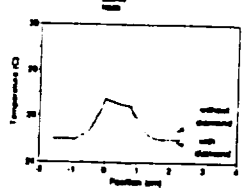
Polycrystalline CVD Diamond



Thermal Conductivity







- o More Efficient Heat Spreaders
- o Lower Device Operating Temperatures
- o Increased Device Reliability/Lifetime
- o Increased Specific Power
- o Elaborate Device Geometries

National Aeronautics and Space Administration
Lewis Research Center

POWER TECHNOLOGY DIVISION

NASA

Space Environment Activity
SAMPIE Shuttle Flight Experiment

1. Serve as principal investigator and project scientist of approved Shuttle flight experiment.
2. Obtained approval for phase C/D flight experiment development.
3. Performing ground tests in plasma interactions facility at LeRC.
4. SAMPIE will space test SSF, APSA, "arc-free", and "electron current choking" designs.

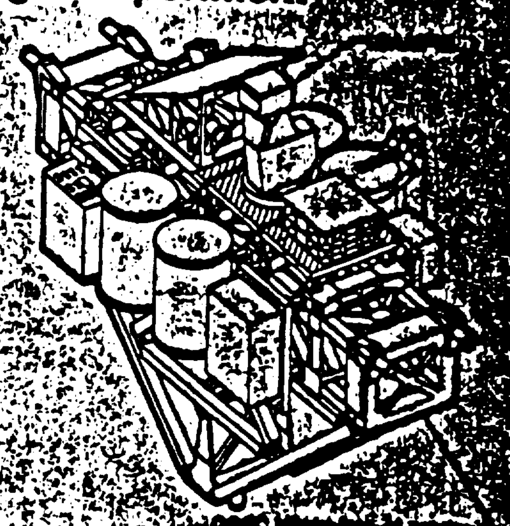
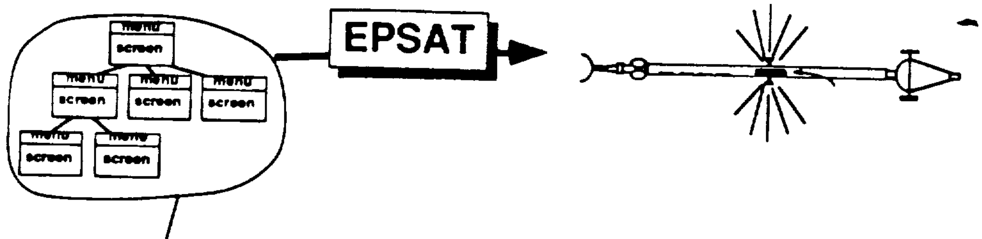


FIGURE: SAMPIE on Hitchhiker pallet in Shuttle bay

MAXWELL

EPSAT
Environment - Power System Analysis Tool



System Design Tool For Large Space Based Power Systems
- System Analysis Of Complex Systems
- Incorporate Many Analysis Models
- Changeable As System Concepts Evolve

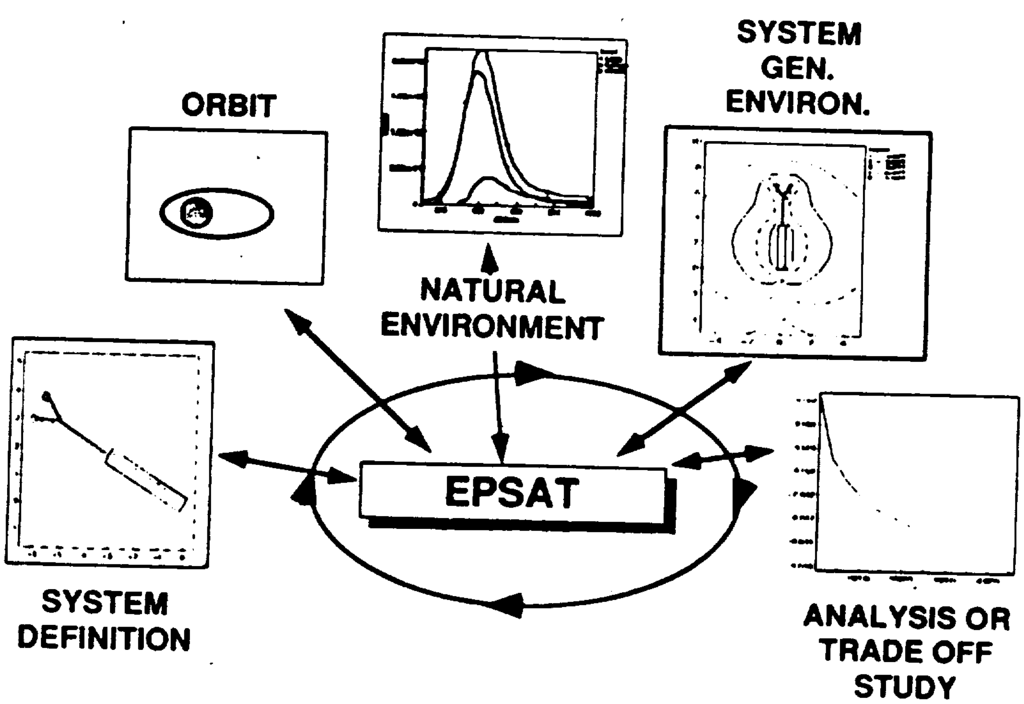
Technology Transfer

Scientists and Engineers → Power System Design Engineers

NASA/Lewis 4/90

MAXWELL

EPSAT Performs Multi - Step Analysis By Connecting *Output* To *Input*



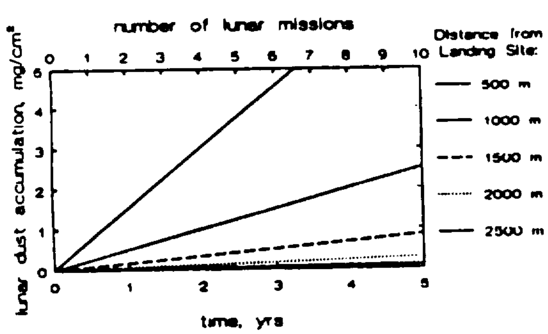
EPSAT - A FOUNDATION FOR SEI

- **EPSAT DEVELOPED UNDER SDIO FUNDING**
  - COMPLETE FOR SDIO ENVIRONMENTS
  - CONSIDERED A MAJOR SUCCESS, AND HAS BEEN EMBRACED BY LARGE COMMUNITY OF MILITARY SPACECRAFT DESIGNERS & ENGINEERS
  - A VERSION CALLED ENVIRONMENTS WORKBENCH IS UNDER DEVELOPMENT FOR SPACE STATION DESIGNERS
- **NEW NASA MISSIONS DEMAND NEW ENVIRONMENT AND EFFECTS MODULES AND VALIDATION THEREOF**
  - LUNAR/MARS BASES
  - NEP/NTP

RWB-91Q.04.30

LUNAR ENVIRONMENTAL INTERACTIONS WITH POWER SYSTEMS

PREDICTED LUNAR DUST ACCUMULATION AFTER MULTIPLE MISSIONS WITH 26,800-N LAUNCH VEHICLE

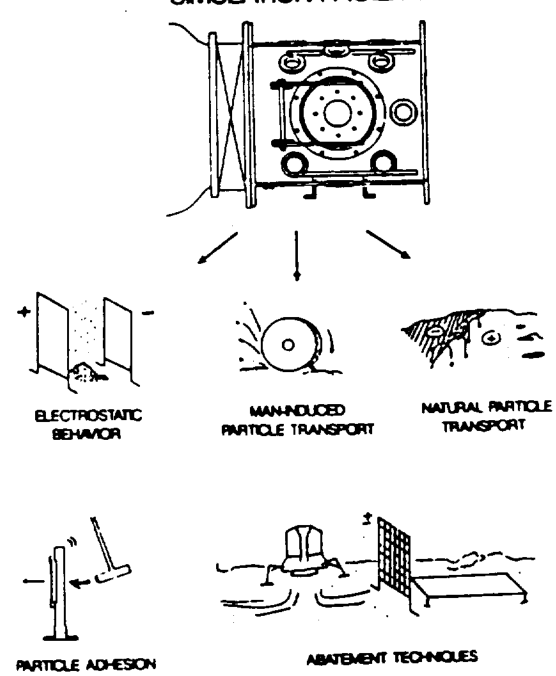


DUST ACCUMULATION PREDICTED TO:

- OCCUR BY SEVERAL MECHANISMS
- BE SIGNIFICANT WITH TIME, DISTANCE
- DRAMATICALLY REDUCE PV PERFORMANCE
- REDUCE RADIATOR PERFORMANCE

THEORETICAL APPROACH

LUNAR ENVIRONMENTAL SIMULATION FACILITY

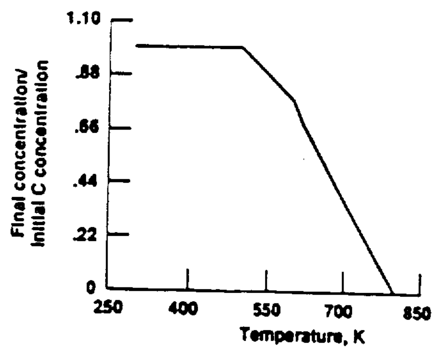


EXPERIMENTAL APPROACH

DURABILITY OF MARTIAN SURFACE POWER SYSTEMS

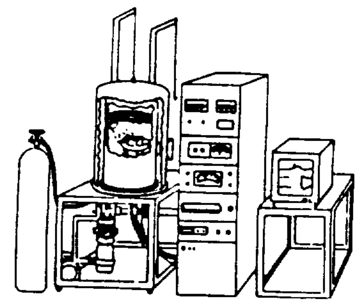
THEORETICAL PREDICTIONS

$C + CO_2 \rightarrow 2\ CO$



EXPERIMENTAL VERIFICATION

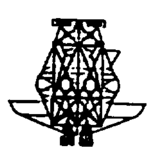
Martian Atmospheric Chemistry
Simulator (MACS)



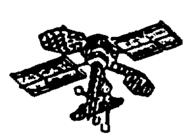
- DUST ACCUMULATION
- AEOLIAN EFFECTS
- CHEMICAL DEGRADATION
- COMPONENT TESTING
- THERMAL CYCLING
- RADIATION DAMAGE
- PASCHEN BREAKDOWN
- ABATEMENT TECHNIQUES

UTILITY POWER FOR SPACE EXPLORATION

- COMBINES SPACECRAFT & TERRESTRIAL ATTRIBUTES
- SPACE INFRASTRUCTURE REQUIRES COMMONALITY WITH DIVERSITY
- REQUIREMENTS AND APPROACH NEED TO BE DEFINED
  - SPACECRAFT DESIGNS INAPPROPRIATE

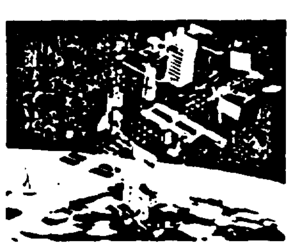


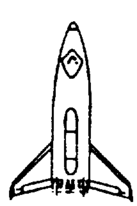
SBOTV



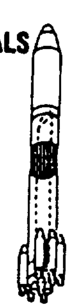
PLATFORM

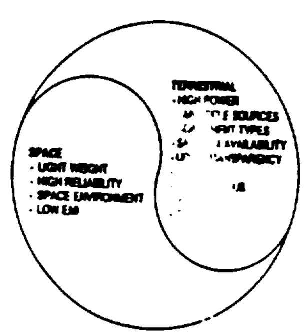
ALS





SHUTTLE II





EXPLORATION MISSIONS

NEW SYSTEMS

- LUNAR/MARS BASE
- SPACE STATIONS
- ROVERS
- ADVANCED LAUNCH SYSTEMS
- TRANSFER VEHICLES (CHEMICAL)
- TRANSFER VEHICLES (NUCLEAR)

NEW TECHNOLOGIES

- NUCLEAR REACTOR
- SOLAR DYNAMIC
- CONVERSION
  - BRAYTON
  - STIRLING
  - RANKINE
- REGEN-FUEL CELL
- FLYWHEEL

CHANGED LOADS

- 1 kW TO >MW
- CONNECTABLE LOADS
  - DIVERSE (SOME LARGE) & > 100
  - >> GEN. CAPACITY
  - LOAD SCHEDULING
- SYSTEM INTERCONNECT
- MOTOR & ELECTRICAL ACTUATOR
  - HIGH REACTIVITY
  - HIGH PEAK POWER
  - REVERSE POWER FLOW

FUTURE POWER SYSTEMS WILL BE VERY DIFFERENT FROM TODAYS SPACECRAFT SYSTEMS

RWB-91Q.02.5

EXPLORATION MISSIONS

GENERIC REQUIREMENTS

- HIGH SAFETY & AVAILABILITY (MANNED SYSTEMS)
- FLEXIBILITY (GROWTH & EVOLVING MISSIONS)
- UNLIMITED POWER SYSTEM LIFE (POWER INTEGRAL TO SYSTEM)
- IN-SITU ASSEMBLY AND SERVICING
- USER TRANSPARENCY (MULTIPLE INDEPENDENT ACTIVITIES)

RWB-91Q.02.6

DEDICATED vs UTILITY POWER SYSTEMS

REQUIREMENTS

CHARACTERISTIC	DEDICATED	UTILITY
Source Capacity	1 -10 kW	kW - MW
Source Number	1 -2	Multiple
Growth	No	Yes
Lifetime	Fixed	Extendible
Repairable	No	Yes
Load/Source Cap.	~ 1	>>1
Physical Size	Small	Large
Flexibility	Loads fixed	Loads vary
Manned	No	Yes

APPROACH

DEDICATED

FOCUS ON MEETING
- MISSION SPECIFIC REQUIREMENTS
- ADAPT EXISTING SPACECRAFT BUS

UTILITY

- FOCUS ON MAJOR SYSTEM ELEMENTS
  - GENERAL REQUIREMENTS
  - FUNCTIONS
  - MUTUAL COMPATIBILITY
- COMBINE MODULAR ELEMENTS
- INCLUDE REQUIREMENTS FOR
  - REPAIRS
  - USER TRANSPARENCY
  - EVOLUTIONARY DEVELOPMENT

**UTILITY APPROACH INCREASES DDT&E COSTS
BUT BROADENS APPLICABILITY AND LOWERS LIFE CYCLE COSTS.**

RWB-910.02.7

SPACE UTILITY SYSTEMS
AC versus DC

- SPACE SYSTEMS - BASED ON DC
- TERRESTRIAL & AIRCRAFT - BASED ON AC
  - HEAVY
  - HIGH FREQUENCY AC DEVELOPED TO REDUCE MASS
- SSF FREQUENCY SELECTION
  - EXTENSIVE TRADE STUDIES
  - DC AND 20 kHz AC TESTBEDS (25 kW)
  - TECHNOLOGY READINESS
  - SELECTED DC (FY91 BUDGET RESTRICTIONS)
    - LOWER DEVELOPMENT COST, LOWER PERFORMANCE
    - HIGHER TRANSPORTATION COSTS
- DATA BASE FOR SPACE EXPLORATION

RWR-910.04.17

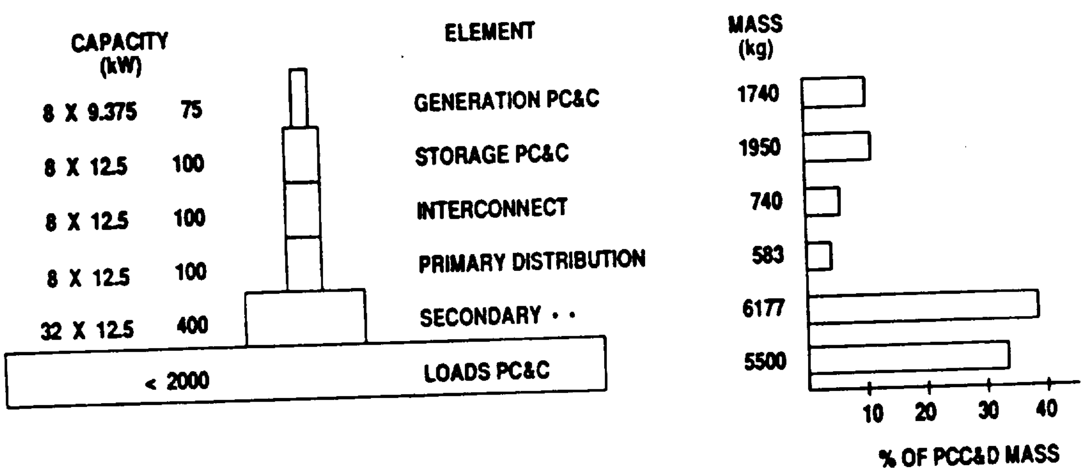
AC versus DC POWER CONDITIONING

- **AC TRADES UP-STREAM COMPLEXITY FOR DOWN-STREAM SIMPLICITY**
  - e.g. INVERTER + TRANSFORMERS vs. DIRECT COUPLE + DC-DC CONVERTER
- **DC ATTRACTIVE FOR SPACECRAFT POWER**
  - DIRECT-COUPLED SOLAR ARRAY
  - SIMPLE DISTRIBUTION & LOAD STRUCTURE (DOWN STREAM)
- **AC ATTRACTIVE FOR SPACE UTILITY**
  - COMPLEX DISTRIBUTION
  - HIGH FANOUT

RWB-91Q.04.18

UTILITY POWER

SUBSYSTEM CAPACITIES & MASSES
(SSF EXAMPLE)



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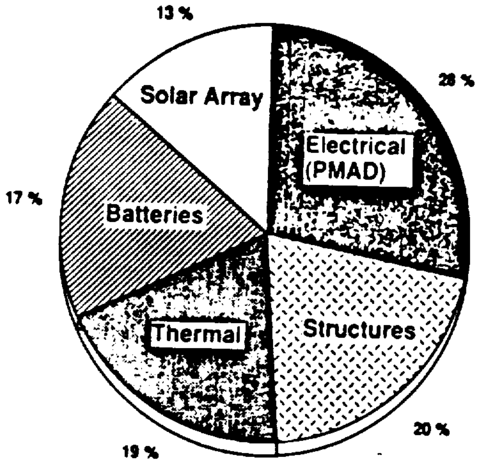
ADVANCED PMAD FOR GROWTH STATION

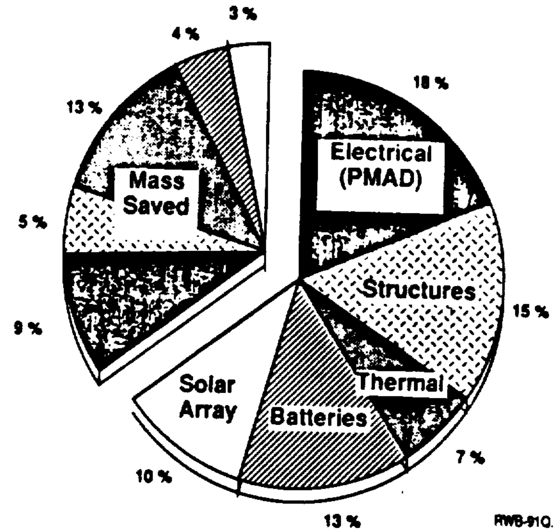
MASS DISTRIBUTION AND SAVINGS



PRESENT POWER SYSTEM MASSES

HIGH FREQUENCY AC AND HIGH TEMPERATURE PMAD COMPONENTS

- LIGHTER PMAD
- HIGHER EFFICIENCY
- REDUCED ARRAYS & BATTERIES
- REDUCED RADIATORS & THERMAL SYSTEMS



RWB-91Q.04.12

NASA C-90-03987

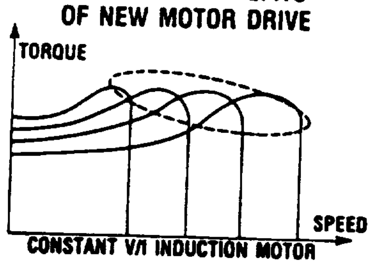
ATD AEROSPACE TECHNOLOGY DIRECTORATE

POWER TECHNOLOGY DIVISION

NASA Lewis Research Center

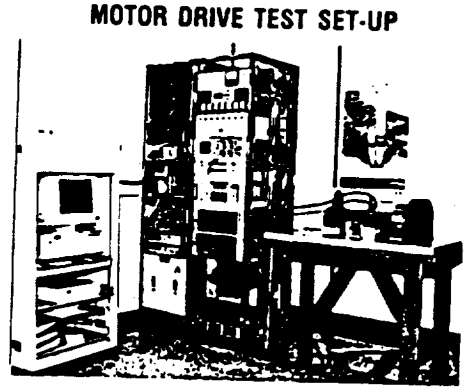
HIGH FREQUENCY LINK, INDUCTION MOTOR DRIVE SYSTEM

PRINCIPLES/BENEFITS OF NEW MOTOR DRIVE



- DEMO 5Hp INDUCTION MOTOR DRIVE
  - —PULSE POPULATION MODULATION FROM HIGH FREQUENCY LINK
  - —FIELD ORIENTED CONTROL
- MAX TORQUE AND EFFICIENCY AT ANY SPEED
- MINIMIZES STRESS ON ELECTRICAL COMPONENTS
- MINIMIZES EMI/EMC

MOTOR DRIVE TEST SET-UP



PAYOFFS FOR LAUNCH VEHICLES AND AIRCRAFT:

- OPERABILITY—LAUNCH ON DEMAND
- REDUCE MAN TESTS, COSTS
- ELIMINATE HYDRAULICS, APU'S, CARTS
- REDUCE WEIGHT, ENERGY

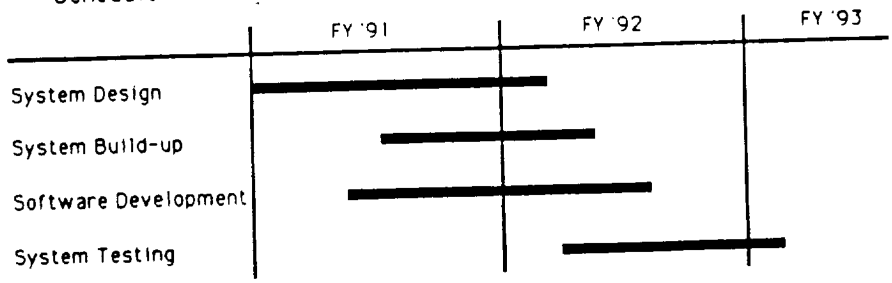
CD-90-46836

POWER TECHNOLOGY DIVISION

LeRC IN-HOUSE EMA

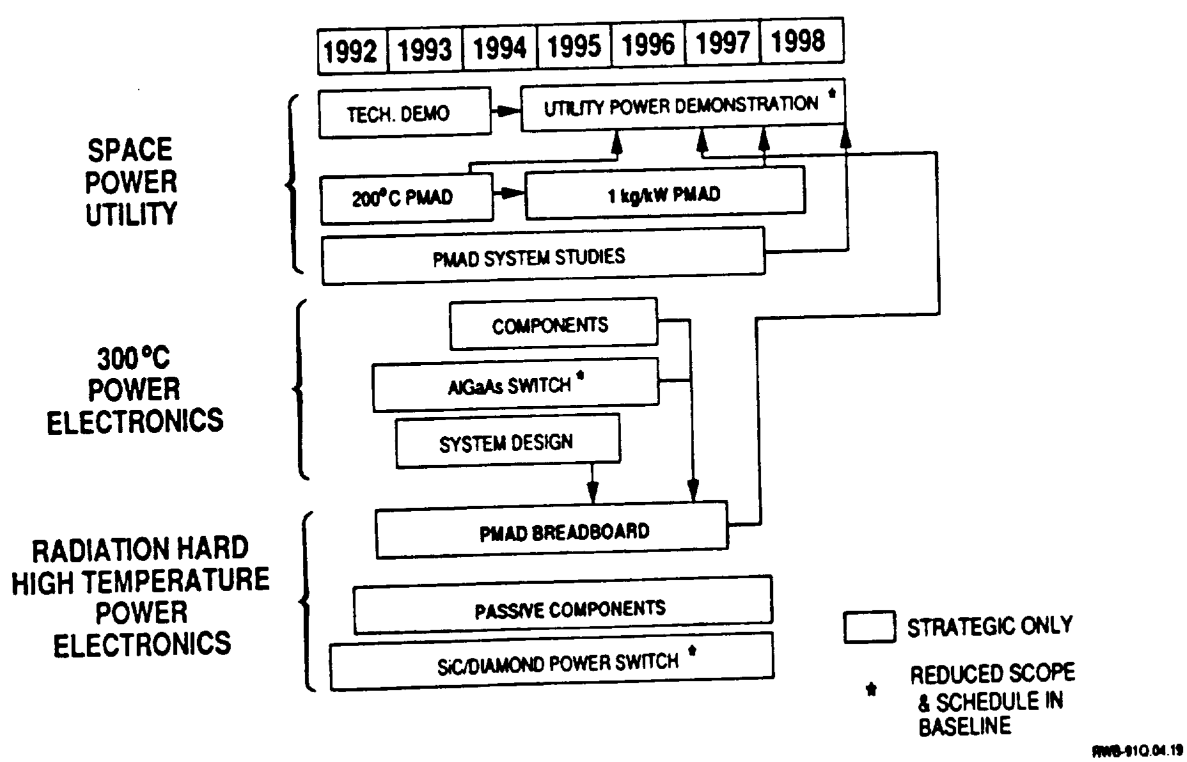
(ELV/ATLAS)

- Joint NASA-General Dynamics exchange program
- 20 Hp nominal, 30 Hp peak induction motor drive system
- BIT (Built-In-Test) capability
  - Phase voltage and current testing
- DSP Control scheme
- Optically coupled, closed loop field oriented control
- Schedule

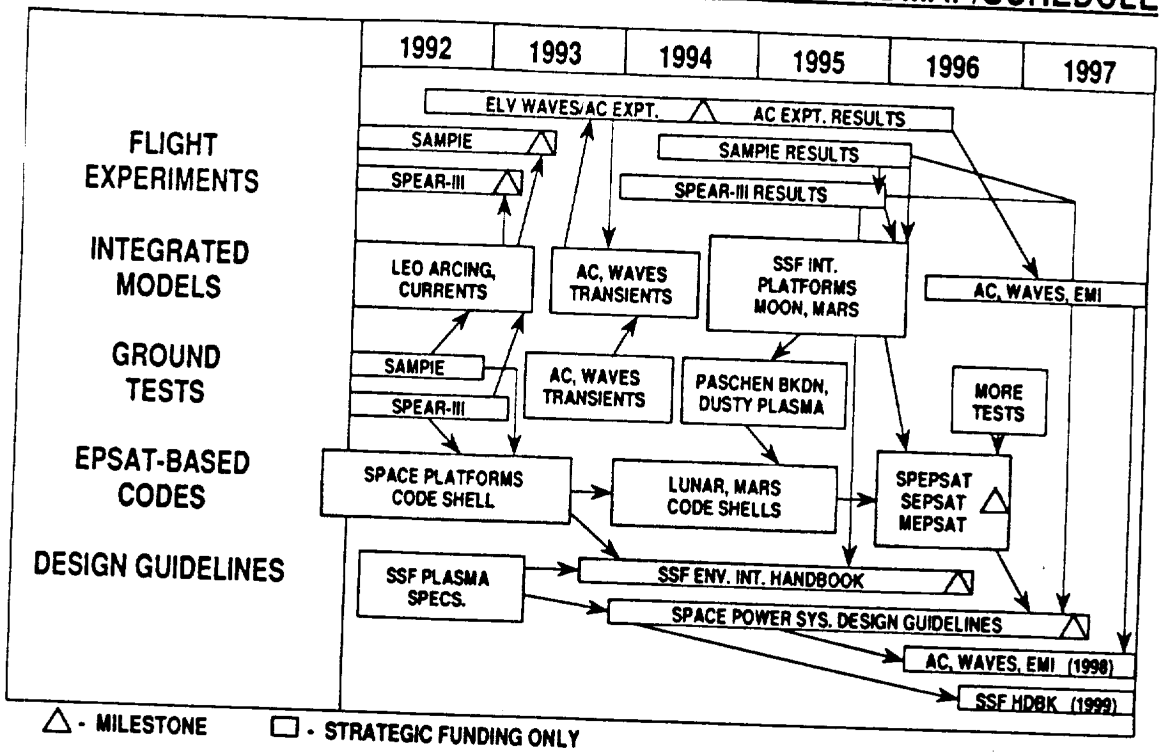


BASE R&T: SPACE ENERGY CONVERSION **POWER MANAGEMENT**

SPACE-UTILITY/HIGH TEMPERATURE PMAD ROADMAP/SCHEDULE



PMAD SPACE ENVIRONMENTAL INTERACTIONS ROADMAP/SCHEDULE



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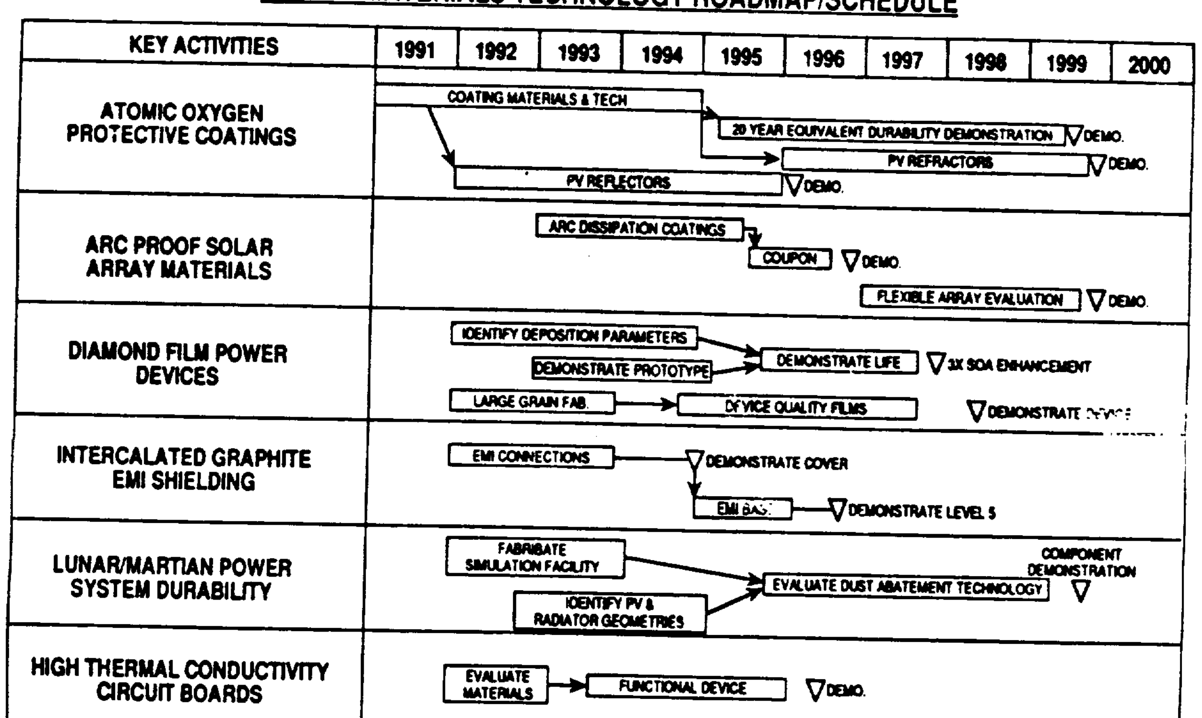
SPACE SCIENCE TECHNOLOGY
POWER MATERIALS TECHNOLOGY

POWER MATERIALS TECHNOLOGY ROADMAP/SCHEDULE



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OAET

POWER INTEGRATION TECHNOLOGY

ROADMAP/SCHEDULE

R&T BASE POWER INTEGRATION TECHNOLOGY		1991	1992	1993	1994	1995	1996	1997	1998	1999	2000
POWER SWITCH HYBRID	CURRENT	HYBRID SWITCH		SMART PROTOTYPE			SMART HYBRID MODULE				MONOLITHIC SMARTS
	AUGMENTED			SMART PROTOTYPE		SMART HYBRID MODULE			MONOLITHIC SMARTS		INTEGRATED SMART POLE
SYNCHRONOUS RECTIFICATION	CURRENT			PROTOTYPE			ADVANCED PROTOTYPE		SMART PROTOTYPE		
	AUGMENTED			PROTOTYPE			ADVANCED PROTOTYPE		SMART PROTOTYPE		INTEGRATED SMART SYNCH. RECT.

JUNE 26, 1991

POWER MANAGEMENT

ACCOMPLISHMENTS - TRANSFERRED TECHNOLOGY

POWER INTEGRATION

- ELECTRONIC SWITCHING (REMOTE POWER CONTROLLER) ADOPTED FOR CRAF

ELECTRICAL COMPONENTS AND SYSTEMS

- DEVELOPED FIRST LARGE POWER TRANSISTOR (D60T) - NOW IN WIDE USE IN DoD AND INDUSTRY
- 150 VDC REMOTE POWER CONTROLLER ADOPTED FOR SSF
- "ROLL RING" ROTARY POWER TRANSFER DEVICE ADOPTED FOR SSF
- HIGH FREQUENCY PMAD ADOPTED FOR SSF (LATER CHANGED TO DC)
- PULSE DENSITY MODULATED DRIVE AND INDUCTION MOTORS ADOPTED FOR ALS TVC AND PRIME CANDIDATE FOR NLS ACTUATORS
- MOSFET CONTROLLED THYRISTOR (MCT) NOW IN PRODUCTION
- FIBER OPTIC CURRENT METER TO BE PRODUCED BY 3M FOR POWER INDUSTRY APPLICATION

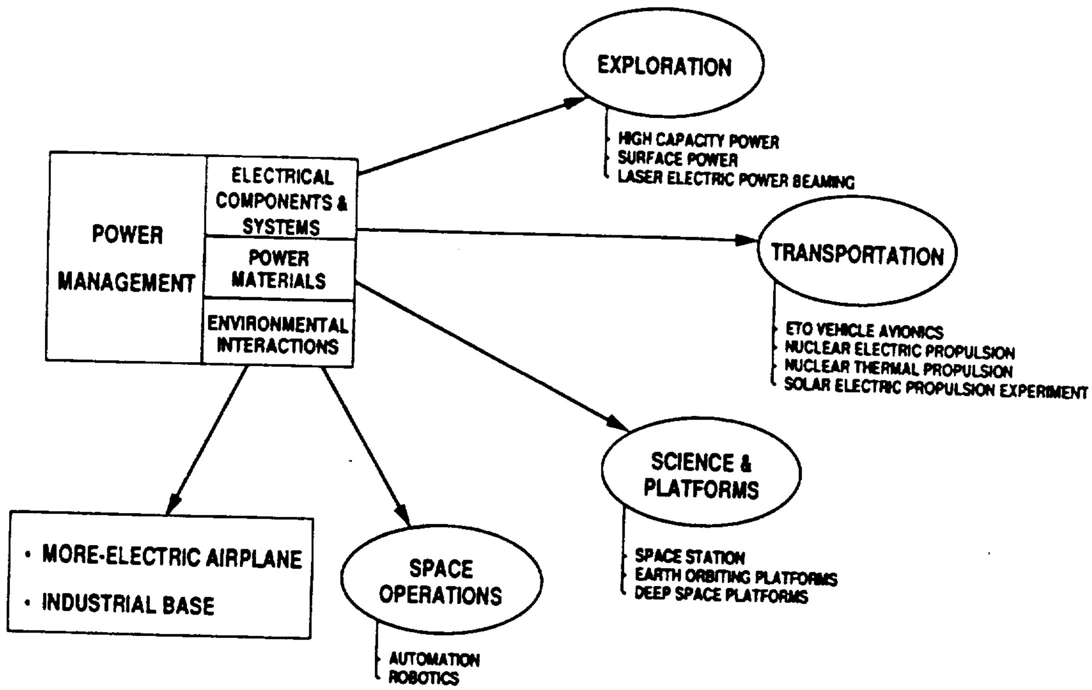
ENVIRONMENTAL INTERACTIONS

- NASCAP IN WIDE USE FOR DESIGN OF GEO SPACECRAFT
- EPSAT IN USE FOR SDIO MISSIONS
- SSF ARRAY DESIGNS BASED ON SAMPIE AND LeRC TESTS
- REVISED "GROUNDING" FOR SSF

POWER MATERIALS

- ATOMIC OXYGEN PROTECTION COATING USED ON SSF ARRAYS
- COATING ALSO BEING EVALUATED FOR BEVERAGE INDUSTRY
- Z93 COATING USED ON SSF RADIATORS
- DIAMOND-LIKE FILMS TO BE USED FOR FACE SHIELDS, HELICOPTER WIND SHIELDS & EYE GLASSES

WIDE APPLICATION TO FOCUSED PROGRAMS



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SUMMARY

- TECHNICAL CHALLENGE: FOR ALL MISSIONS, PMAD INTEGRATES POWER SUBSYSTEM WITH THE TOTAL SYSTEM AND SATISFY ITS REQUIREMENTS. NEW TECHNOLOGY IS REQUIRED TO:
  - MEET EMERGING NEEDS OF NEW MISSIONS: BASES, ROVERS, PLATFORMS, VEHICLES
  - REDUCE PMAD MASS AND COST (NOW 1/2 - 1/4 THOSE OF POWER SYSTEM)
  - INCREASE SYSTEM SAFETY, LIFE, FLEXIBILITY AND USABILITY
- APPROACH: MUST ADDRESS EXTREMELY COMPLEX SET OF ISSUES, MULTIPLE TECHNOLOGIES AND A MASSIVE COMMERCIAL INFRASTRUCTURE
  - FOUR INTERLINKED RESEARCH GROUPS WITH DIFFERENT SPECIALTIES
  - SYSTEM ANALYSIS TO IDENTIFY ISSUES AND QUANTIFY BENEFITS
  - COMMERCIAL DEVELOPMENT & MARKET SERVE AS PROGRAM AMPLIFIERS
- PAYOFF: IMPACTS ALL MISSIONS, EITHER ENABLING OR ENHANCING
  - SIGNIFICANTLY REDUCED MASS AND COST
  - GREATER SAFETY, RELIABILITY AND LIFETIME
  - FLEXIBLE AND USER FRIENDLY POWER SYSTEMS
  - CONFIDENT SYSTEM DEVELOPMENT
- FUNDING AUGMENTATION NEEDED TO ASSURE THAT ALL CRITICAL ISSUES ARE ADDRESSED AND TECHNOLOGY INFRASTRUCTURE IS AVAILABLE WHEN NEEDED
- PMAD PROGRAM IMPACTS ALL FOCUS THRUSTS AND 12 THRUST ELEMENTS
  - STRONG SYNERGISM WITH AERONAUTICS, DoD PROGRAMS AND COMMERCIAL APPLICATIONS

RWB-91Q.04.31

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INTEGRATED TECHNOLOGY PLAN
EXTERNAL REVIEW
-JUNE 26, 1991-

BASE R & T PROGRAM

THERMAL MANAGEMENT

(506-41-51)

T. D. SWANSON GODDARD SPACE FLIGHT CENTER

BASE R&T PROGRAM

SPACE ENERGY CONVERSION R&T

OAET

THERMAL MANAGEMENT

• OBJECTIVES

• PROGRAMATIC

DEVELOP ADVANCED ORBITAL AND PLANETARY THERMAL CONTROL TECHNOLOGIES WITH LOW MASS, HIGH RELIABILITY, AND LONG LIFE

• TECHNICAL

HEAT PUMPS 7 KG/KW
RADIATOR MASS 1 - 4 KG/M2
CRYOGENIC HEAT PIPES 3X
POWER ELECTRONICS 1/20

• SCHEDULE

- 1992 DEMONSTRATE LIQUID SHEET RADIATOR
- 1995 DEMONSTRATE 2X SOA IMPROVEMENT IN CRYOGENIC HEAT PIPES
- 1996 DEMONSTRATE ADVANCED HEAT PUMPS (3X SOA) SUITABLE FOR MICRO G
- 1997 COMPLETE INTEGRATED TEST FOR POWER ELECTRONICS RADIATOR
- 1999 VALIDATE ANALYTICAL MODELS FOR HEAT PUMPS AND HEAT PIPES

• RESOURCES

YEAR	CURRENT	STRATEGIC
• 1993	$ 1.0M	$ 1.1M
• 1994	$ 1.1M	$ 1.4M
• 1995	$ 1.1M	$ 1.7M
• 1996	$ 1.2M	$ 1.9M
• 1997	$ 1.2M	$ 2.3M
• 1998	$ 1.3M	$ 2.6M
• 1999	$ 1.3M	$ 3.0M

• PARTICIPANTS

• GODDARD SPACE FLIGHT CENTER

RESPONSIBILITY INCLUDES THERMAL CONTROL OF INSTRUMENTATION, SENSORS, AND OTHER HEAT DISSIPATING EQUIPMENT

• LEWIS RESEARCH CENTER

RESPONSIBILITY INCLUDES ADVANCED RADIATOR CONCEPTS AND ADVANCED POWER ELECTRONICS COOLING

PROGRAM SCOPE

OAET

THE THERMAL MANAGEMENT BASE R & T PROGRAM WILL SUPPORT FUTURE ORBITAL, DEEP SPACE, AND PLANETARY MISSIONS BY DEVELOPING A BROAD, GENERIC TECHNOLOGY BASE IN NEW THERMAL CONTROL SYSTEMS AND COMPONENTS.

CURRENT THERMAL MANAGEMENT SITUATION

OAET

THERMAL CONTROL TECHNOLOGY IS CURRENTLY EXPERIENCING A MAJOR GROWTH IN REQUIREMENTS. THIS IS DRIVEN BY MAJOR INCREASES IN SPACECRAFT:

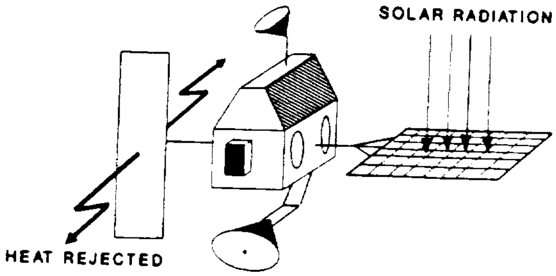
* PHYSICAL SIZE
* POWER LEVEL
* COMPLEXITY

EVOLUTION OF TECHNOLOGY FROM DISCRETE TO CENTRAL THERMAL CONTROL

IMPLICATIONS INCLUDE:

* NOW ENABLING TECHNOLOGY (EOS PLATFORM)
* GREATER RISK; FAILURE NOT GRADUAL, MAY CAUSE LOSS OF SPACECRAFT

GROWTH IN SIZE



POWER IN = HEAT REJECTED

SUBSYSTEM	TRENDS	ISSUES	SOLUTIONS
POWER	HIGHER LEVELS	GREATER SIZE AND WEIGHT	• HIGHER EFF. CELLS • NEW GENERATOR CONCEPTS
THERMAL	HIGHER POWER, TIGHTER LIMITS, LONGER DISTANCES	• SIZE/WEIGHT • CONTROL	• HEAT PUMPS • TWO-PHASE BUS • NEW RADIATOR CONCEPTS

GROWTH IN COMPLEXITY

BUILDINGS/SPACECRAFT ANALOGY

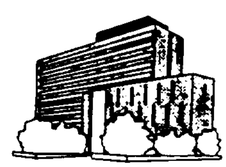
1800's

Fireplace and Windows

Early-Mid 1900's

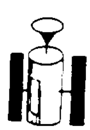
Furnace and Windows

Today



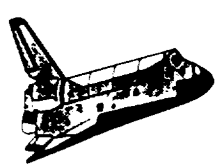
Central, multi-zone heating and cooling

1960's and 1970's



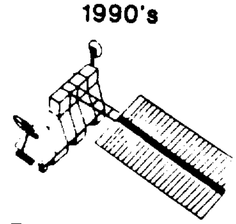
MLI and heaters

1980's

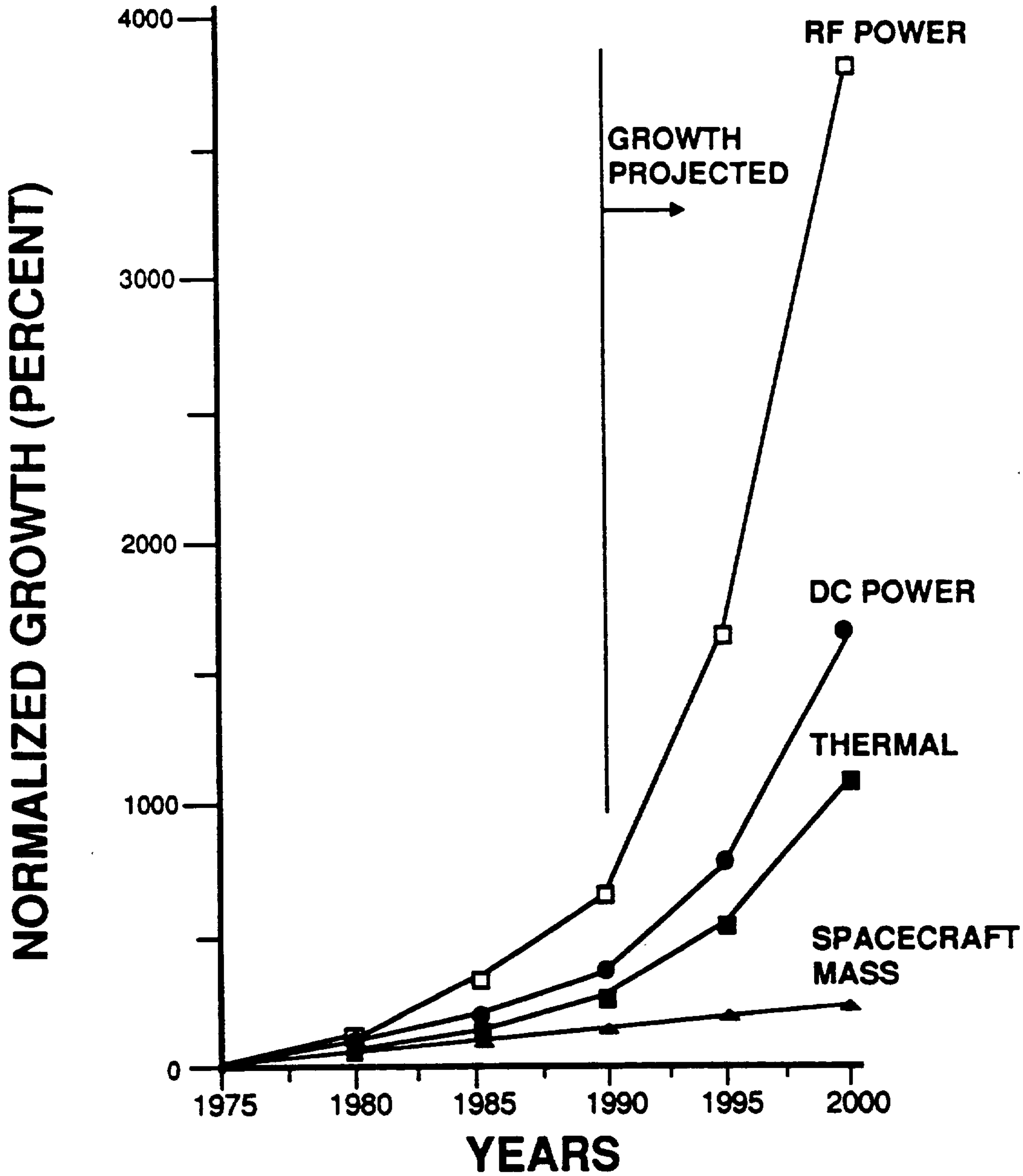


Pumped single phase and heat pipes

1990's

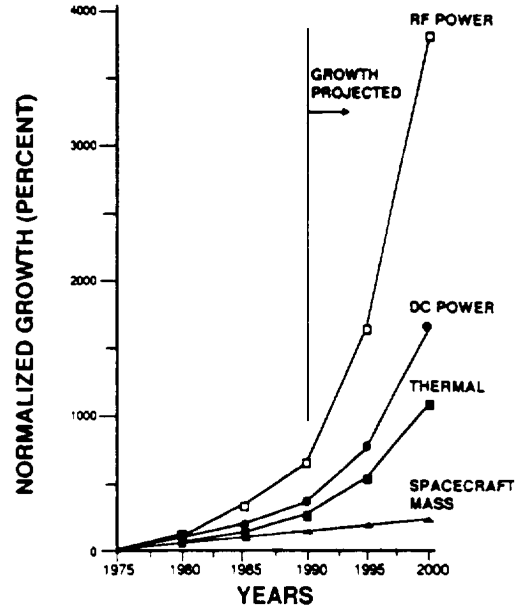


Two-phase central thermal bus



	BASELINE	CURRENT	PROJECTED
YEAR	1975	1990	2000
MASS (KG)	940	1300	1950
DC (W)	850	3750	15000
RF (W)	180	1350	7000
THERMAL DISSIPATION (W)	670	2400	8000

DOD PREDICTIONS



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THERMAL DISSIPATION (W)	670	2400	8000

DOD PREDICTIONS

APPROACH

OAET

PROGRAMMATIC ELEMENTS FOR ACCOMPLISHING THIS EFFORT INCLUDE THE FOLLOWING:

* MISSION FOCUSED SYSTEMS LEVEL ANALYSIS STUDY TO IDENTIFY NEEDS
* MULTI-CENTER PARTICIPATION
* LEVERAGE WITH DOD, DOE AND OTHER NASA EFFORTS (SBIR, IN-STEP EXPERIMENTS, PROJECT SUPPORTED WORK)
* TRANSITION FROM OAET SUPPORT TO PROJECT SUPPORT AS TECHNOLOGY MATURES
* 10 TO 15 YEAR LEAD TIME NEEDED
* PURSUE MULTIPLE TECHNOLOGY OPTIONS (FOR STRATEGIC LEVEL OF FUNDING)

TECHNOLOGY NEEDS

OAET

ANALYSIS OF FUTURE MISSIONS, SUCH AS SECOND GENERATION EOS PLATFORMS, LUNAR BASE, MARS MISSION, AND CRAF/CASSINI, INDICATE THE FOLLOWING FUTURE REQUIREMENTS:

- GREATER POWER LEVELS
- MORE HEAT LOAD SOURCES
- HEAT LOADS BURIED WITHIN BODY OF THE SPACECRAFT WITH NO VIEW TO SPACE
- CONFLICT BETWEEN RADIATOR VIEWS AND INSTRUMENT VIEWS
- GREATER TRANSPORT LENGTHS
- TIGHTER TEMPERATURE CONTROL
- INCREASED CRYOGENIC TEMPERATURE CONTROL
- HIGHER RELIABILITY
- LOWER WEIGHT

TECHNOLOGY OPTIONS

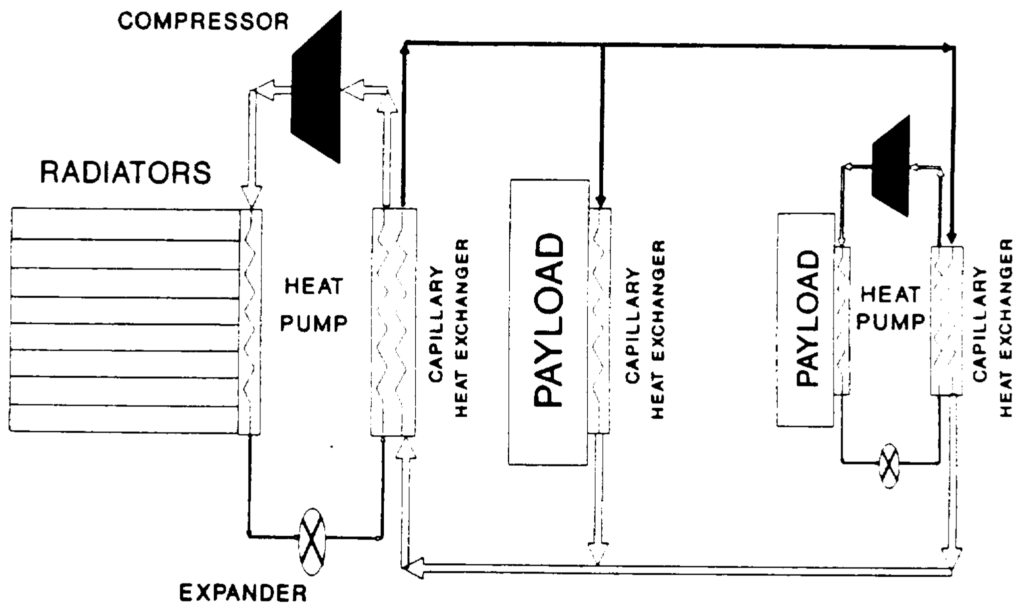
OAET

TECHNOLOGY	HARDWARE/SOFTWARE NEEDED
• CENTRAL TWO-PHASE BUS	• HEAT PUMPS • ANALYTICAL MODEL OF FLUIDS IN MICRO-GRAVITY • LONG LIFE MECHANICAL PUMPS FOR AMMONIA • PUMP CONTROLLER • UNDERSTANDING OF NON-CONDENSABLE GAS ISSUE • LIGHT WEIGHT MATERIALS
• REDUCED RADIATOR AREA/WEIGHT	• COMPOSITE RADIATORS • INNOVATIVE CONCEPTS • HEAT PUMPS • ELIMINATE NEED FOR EXTERNAL POWER ELECTRONICS RADIATOR • LIQUID METAL MICRO HEAT PIPE • DIRECT IMMERSION HEAT PIPE

HEAT PUMP TWO-PHASE BUS CONCEPT

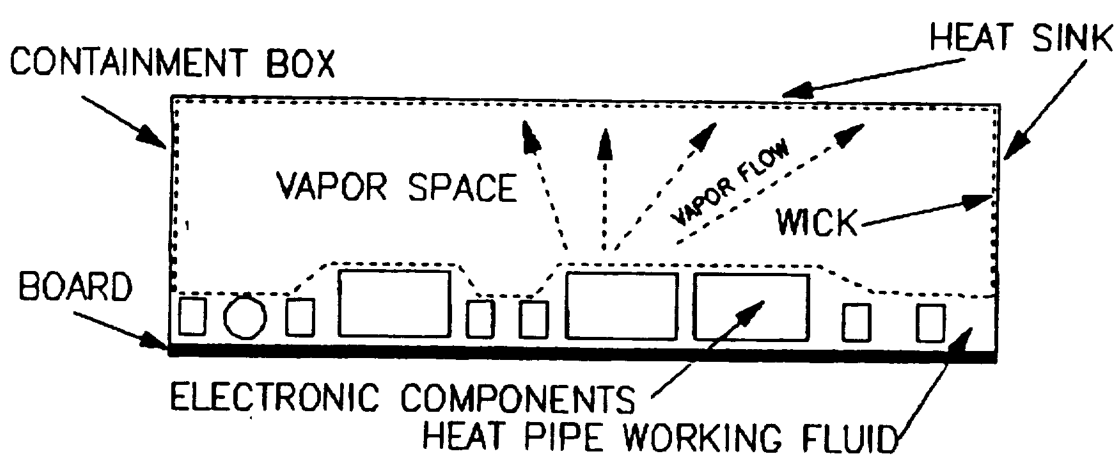
-INCREASE REJECTION TEMPERATURE/COOL PAYLOAD-

OAET

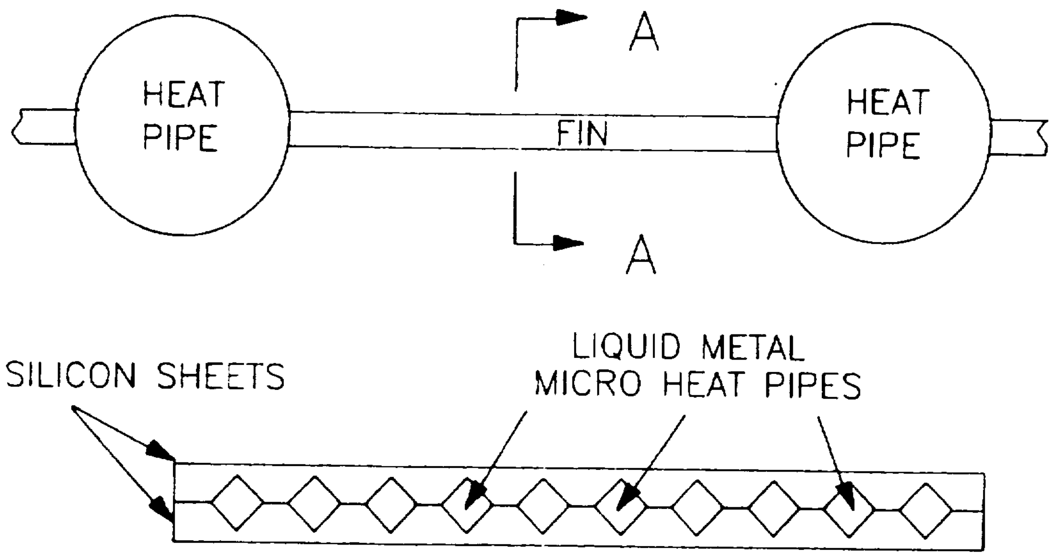


POWER TECHNC GY DIVISION

DIRECT IMMERSION HEAT PIPE



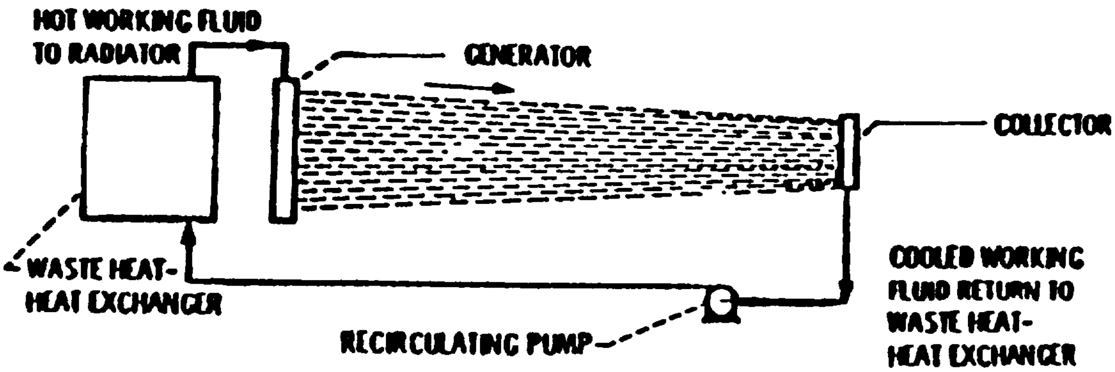
LIQUID METAL MICRO HEAT PIPE FINS



SECTION A – A

LIQUID DROPLET AND LIQUID SHEET RADIATOR

RADIATIVE "FINS" AND "HEAT PIPES" OF CONVENTIONAL RADIATORS REPLACED BY STREAMS OF DROPLETS OR A LIQUID SHEET



TECHNOLOGY OPTIONS
(CONTINUED)

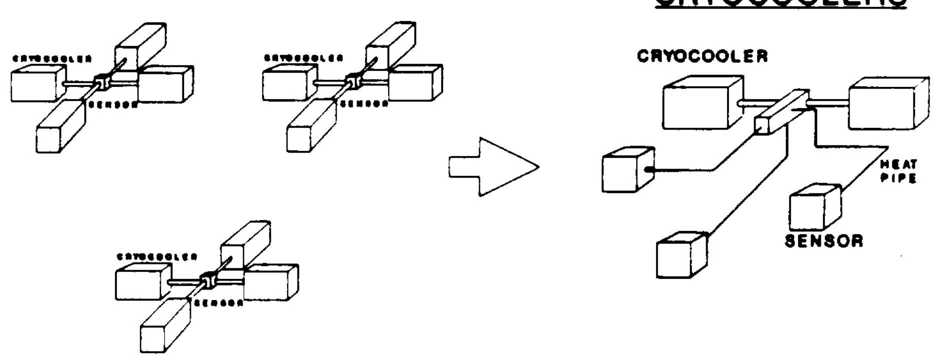
OAET

TECHNOLOGY	HARDWARE/SOFTWARE NEEDED
LOW TEMPERATURE THERMAL CONTROL	• CRYOGENIC HEAT PIPES • ANALYTICAL MODEL • CRYOGENIC TWO-PHASE BUS • THERMAL SWITCH
HIGH TEMPERATURE THERMAL CONTROL	• HIGH TEMPERATURE HEAT PIPES • ANALYTICAL MODEL • MATERIALS

CRYOGENIC HEAT PIPE APPLICATION

OAET

INDIVIDUALLY COOLED SENSORS | CENTRAL BANK OF CRYOCOOLERS



THREE SENSORS,
12 CRYOCOOLERS

THREE SENSORS,
2 TO 6 CRYOCOOLERS

TECHNOLOGY PAYOFF

OAET

- ENABLE CERTAIN MISSIONS
  - LUNAR BASE (LOW TEMPERATURE (<300 K) HEAT REJECTION)
  - ADVANCED ORBITAL PLATFORMS
- ENHANCE SCIENCE RETURN
  - LOWER WEIGHT FOR SUBSYSTEMS MEANS MORE WEIGHT AVAILABLE FOR SCIENCE PAYLOAD
  - LONGER LIFE/MORE RELIABLE THERMAL CONTROL WILL ALLOW LONGER MISSIONS
- ENABLE LARGER/MORE COMPLEX COMMERCIAL SATELLITES

STATE OF THE ART VS. GOALS

OAET

TECHNOLOGY	STATE OF THE ART	GOAL
HEAT PUMP	24 KG/KW	8 KG/KW
CRYO HEAT PIPE	10 W-m @ 70 K	20 W-m @ 70 K
LIGHTWEIGHT RADIATOR	9 KG/M2	1-4 KG/M2
ANALYTICAL MODELS FOR ENGINEERING PARAMETERS	N/A	VERIFIED BY MICRO-GRAVITY DATA
POWER ELECTRONICS RADIATOR	6 M2/KW	0.3 M2/KW
MECHANICAL PUMP	500 HOURS LIFE	80,000 HOURS LIFE

PROGRAM DESCRIPTION
-RECENT ACCOMPLISHMENTS-

OAET

- OXYGEN AND NITROGEN CRYOGENIC HEAT PIPES
  -FABRICATED AND TESTED, GOOD CORRELATION TO MODEL
- CRYOGENIC HEAT PIPE FLIGHT EXPERIMENT
  -UNDERGOING PERFORMANCE TESTING, OCTOBER 1992 MANIFEST, JOINT EXPERIMENT WITH AIR FORCE (WRIGHT LABORATORY)
- HEAT PUMPS
  -COMPLETED SYSTEM LEVEL STUDY, INITIATED COMPONENT LEVEL CONCEPTUAL DESIGN AND SPECIFICATION (LEVERAGED EFFORT WITH NIST)
- LIGHTWEIGHT MATERIALS
  -COMPLETED SOA SURVEY, IDENTIFIED SEVERAL PROMISING CANDIDATES
- TWO-PHASE LOOPS
  -INITIATED INNOVATIVE CONTROLLER STUDY AND TEST

PROGRAM DESCRIPTION
-CURRENT AND STRATEGIC-

OAET

TECHNOLOGY	.ESTONE	SCHEDULE
HEAT PUMPS	• DEVEL(TWO (*ONE*) BASIC DESIGN ,ONCEPTS	• 1994
	• 3X SOA (*2X SOA*) IMPROVE-MENT ' SPECIFIC WEIGHT	• 1996/ *1997*
	• DESIGN -IGHT EXPERIMENT	• 1999/ *2001*
CRYOGENIC HEAR PIPES	• 50% (*35%*) IMPROVEMENT OVER SOA	• 1995
	• DESIGN FLIGHT EXPERIMENT	• 1998
LIGHTWEIGHT RADIATORS	• IDENTIFY INNOVATIVE CONCEPTS	• 1994
	• *CONSTRUCT MICRO HEAT PIPE FINS*	• *1995*
	• DEMONSTRATE 1-4 KG/M2 (*3-5 KG/M2*) RADIATOR	• 1996

NOTE: ITALICS REFERS TO REDUCTION IN SCOPE/PERFORMANCE IF STRATEGIC FUNDING LEVEL IS NOT APPROVED

PROGRAM DESCRIPTION-CONTINUED
-CURRENT AND STRATEGIC-

OAET

TECHNOLOGY	MILESTONES	SCHEDULE
POWER ELECTRONIC THERMAL CONTROL	• DEVELOP INNOVATIVE CONCEPTS	• 1993
	• 20:1 REDUCTION IN SIZE AND WEIGHT OF RADIATOR	• 1997
CRYOGENIC TWO-PHASE THERMAL BUS	• DESIGN CONCEPT	• 1995/ *1997*
	• GROUND TEST	• 1998/ *2000*
CODE VALIDATION	• WATER HEAT PIPE	• 1994/ *1997*
	• LIQUID METAL HEAT PIPE	• 1996/ *1997*
LIGHTWEIGHT MATERIALS	• 35% (*20%*) REDUCTION IN WEIGHT OF COMPONENTS	• 1997
ANALYTICAL MODEL	• CRYOGENIC HEAT PIPES	• 1996/*1998*
	• HEAT PUMPS	• 1999/*2002*

RESOURCE REQUIREMENTS
($ M)

OAET

	1991	1992	1993	1994	1995	1996	1997
CURRENT	0.7	1.0	1.0	1.1	1.1	1.2	1.2
3X	0.7	1.0	1.1	1.4	1.7	1.9	2.3
STRATEGIC	0.7	1.0	1.1	1.4	1.7	1.9	2.3

RELATIONSHIP OF R & T BASE TO FOCUSED PROGRAM

OAET

FOCUSED PROGRAM ENHANCES BASE PROGRAM BY;

- PROVIDING MORE TECHNICAL OPTIONS FOR A GIVEN COMPONENT
- PROVIDING MORE SPECIFIC DESIGN AND ANALYSIS OF ISSUES FOR A GIVEN MISSION CLASS
- IMPROVING PERFORMANCE MARGIN
- ACCELERATING DEVELOPMENT SCHEDULE

RELATED TECHNOLOGY EFFORTS

OAET

NASA

- EOS AND SPACE STATION PROJECTS
  - -40 C TWO-PHASE THERMAL BUS CONCEPTS
- IN-STEP
  - -GREGORIG GROOVE HEAT EXCHANGER
  - -LIQUID MOTION IN A TANK
- SBIR
  - -MECHANICAL/CHEMICAL HEAT PUMP
  - -SINTERED WICK CRYOGENIC HEAT PIPE
  - -LONG LIFE MECHANICAL PUMP
  - -COMPOSITE RADIATOR

AIR FORCE

- JOINT CRYOGENIC HEAT PIPE EXPERIMENT WITH NASA/GSFC
- HIGH TEMPERATURE HEAT PIPE
- ANALYTICAL MODEL FOR HEAT PIPES
- CAPILLARY PUMPED LOOPS

DOE

- ADVANCED HEAT ENGINES (STIRLING, ABSORPTION)

-SUMMARY-
R&T BASE: THERMAL MANAGEMENT

OAET

- TECHNICAL CHALLENGES: MICRO G PERFORMANCE, COST, LIFETIME
- APPROACH: FOCUS ON HEAT PUMPS, CRYOGENIC HEAT PIPES, INNOVATIVE RADIATORS, 20:1 REDUCTION FOR POWER ELECTRONICS RADIATOR, AND ANALYTICAL MODELS
- PAYOFF: ENABLE LUNAR BASE (300 K WASTE HEAT REJECTION), MAJOR IMPROVEMENT IN SENSOR COOLING, 50% OR MORE REDUCTION IN RADIATOR SIZE AND SPECIFIC MASS, AND BETTER ANALYTICAL MODELS
- AUGMENTATION RATIONALE: EXPAND BASE PROGRAM TO INCLUDE MULTIPLE OPTIONS, ADDRESS PROBLEMS NOT ADDRESSED IN BASE
- RELATIONSHIP TO OTHER PROGRAMS: BASE PROGRAM PROVIDES GENERIC FOUNDATION FOR MORE MISSION SPECIFIC FOCUSED EFFORT, SIGNIFICANT INTERACTION WITH AIR FORCE
- TECHNOLOGY CONTRIBUTIONS: CODE R FUNDED CAPILLARY PUMPED LOOP TECHNOLOGY NOW BASELINED FOR EOS PLATFORM - ENABLING TO THIS MISSION

SPACE NUCLEAR POWER (SP-100)

BY

R. J. SOVIE
DEPUTY CHIEF, POWER TECHNOLOGY DIVISION
NASA LEWIS RESEARCH CENTER

ITP EXTERNAL REVIEW

JUNE 27 1991

WHAT WE WILL DISCUSS

- OBJECTIVES/BENEFITS
- SP-100 BACKGROUND
- SCALING
- SP-100 GROUND ENGINEERING SYSTEM STORY
  - TECHNICAL CONTENT
  - PROGRAMMATICS
  - SP-100 REVIEW GROUP
  - PRESENT SCHEDULE
- TECHNICAL PROGRESS
- CONCLUDING REMARKS

ITP.RJS91-002.2

Space Nuclear Power

OBJECTIVES

- **Programmatic**

  Develop and Validate Technologies for Safe and Reliable Nuclear Power Systems to Support Lunar Outpost and Mars Exploration Missions

- **Technical**

  Power Level - 100 + kilowatts (nominal)
  Specific Mass - 30 - 50 kilograms per kilowatt
  Operations - Space- and Surface basable
  Life Time - 7 years at full power

SCHEDULE

- 1993 Thermoelectric Cell Fabricated and Tested in Relevant Thermal Environment
- 1994 NAT Fuel Pins Fabricated & In Storage
- 1995 Restart Nuclear Assembly Test Site
- 1996 Thermoelectric Converter/Electromagnetic Pump Subsystem Performance Testing Complete
- 2001 Complete Flight-Like Integrated Assembly Test and Nuclear Assembly Test for Lunar Outpost Nuclear Power Systems

RESOURCES*

CURRENT		STRATEGIC/3X	
1991	$ 10.0 M	1991	$ 10.0 M
1992	$ 20.0 M	1992	$ 20.0 M
1993	$ 25.0 M	1993	$ 25.0 M
1994	$ 25.0 M	1994	$ 25.0 M
1995	$ 20.0 M	1995	$ 26.0 M
1996	$ 20.0 M	1996	$ 27.0 M
1997	$ 20.9 M	1997	$ 28.0 M

*Note: *This Element Provides NASA's Contribution To The Ongoing NASA, DoD, DoE, SP-100 Program. Resources Shown are NASA's Contribution Only.*

PARTICIPANTS

- **Jet Propulsion Laboratory**
  Lead for SP-100 Ground Engineering System Project, Responsible for Component Technologies, Project Management
- **Lewis Research Center**
  Space Subsystems, Materials
- **Los Alamos National Laboratory**
  Lead for Reactor Systems/Fuel Development
- **Contractors**
  General Electric

ITP.RJS91-002.12

SPACE NUCLEAR POWER
SP-100

- **SP-100**
  - NATIONAL PROGRAM
  - DOE/NASA/DOD

TO DEVELOP SPACE REACTOR POWER SYSTEMS AT THE 10 kWe to 1 MWe POWER LEVELS FOR USE IN FUTURE MILITARY AND CIVILIAN SPACE MISSIONS

ITP.RJS91-002.3

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POWER TECHNOLOGY DIVISION

ADVANCED TECHNOLOGY GOALS

		W/kg		
		LEO	MARS	LUNAR
PHOTOVOLTAICS	- 300 W/kg ARRAYS	16	NA	NA
BATTERIES	- 100 W-hr/kg			
REGEN. FUEL CELLS	- 1000 W-hr/kg	–	8	3
ADVANCED SOLAR DYNAMICS		16 < AREA	8	3
NUCLEAR REACTOR POWER SYSTEMS		25 - 40	←25 - 65→	
ROVERS, VEHICLES			← 5 - 10 →	

NASA

LeRC

SURFACE POWER SYSTEM MASS DRIVERS

SPACE STATION

~ 60 MIN. LIGHT/30 MIN. DARK

LUNAR

~ 14 DAY DAY/NIGHT CYCLE

MARS

~ 12 HR DAY/NIGHT CYCLE

STORAGE

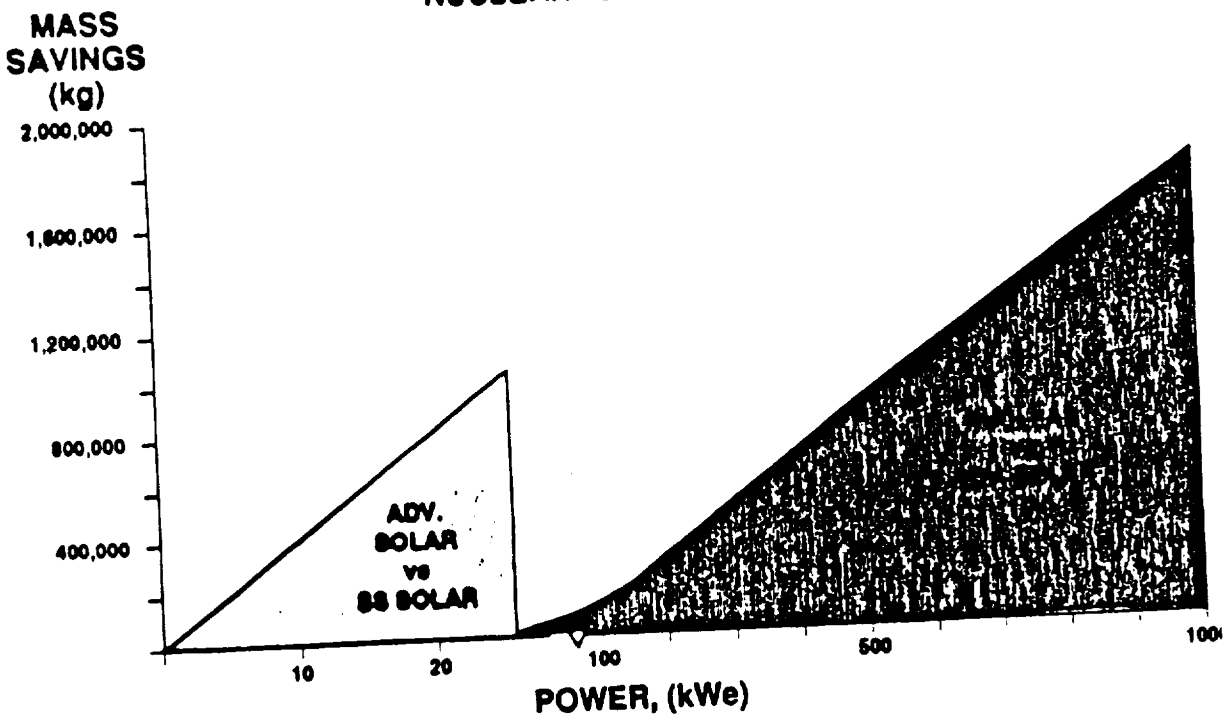
BATTERIES

⇒ REGENERATIVE FUEL CELLS

⇒ NUCLEAR

MASS SAVINGS IN LEO

ADV. SOLAR vs SPACE STATION SOLAR
NUCLEAR vs ADV. SOLAR



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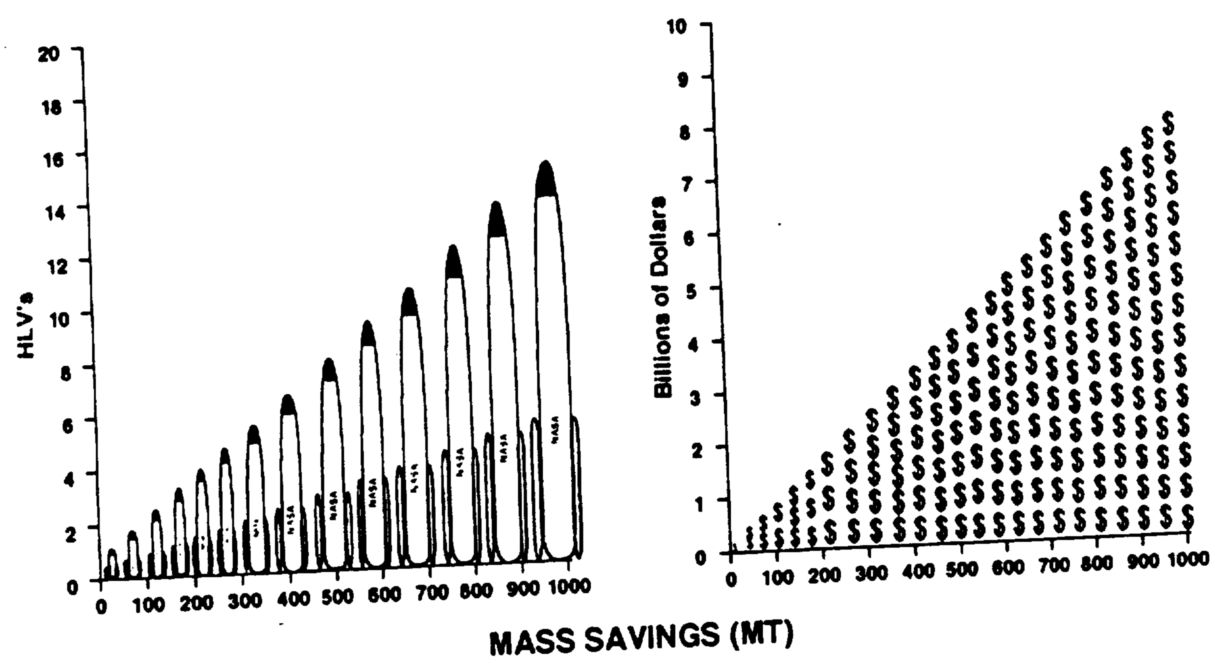
MASS SAVINGS BENEFITS



SPACE NUCLEAR POWER
SP-100

PROVIDES TECHNOLOGY FOR:

SPACE EXPLORATION

LUNAR, MARS SURFACE POWER

NEP PRECURSOR MISSIONS

SCIENCE

1 - 100 kWe NEP

TRANSPORTATION

1 - 40 MWe NEP CARGO , MANNED, & MARS TRANSFER VEHICLES

SPACE NUCLEAR POWER
SP-100 KEY REQUIREMENTS

- SCALABLE: 10's TO 100's OF kWe
- LIFETIME: 7 YEARS FULL POWER - 10 YEAR LIFE (15)
- SAFE FOR ALL MISSION PHASES
- RADIATION SHIELDED TO PROTECT PAYLOAD
- SURVIVABLE
- SPACE SHUTTLE AND ELV COMPATIBLE
- ~ 25 W/kg AT 100 kWe (80 W/kg)

ITP.RJS91-002.4

SP-100 BACKGROUND

ITP RJS91-002.6

LeRC

SP-100

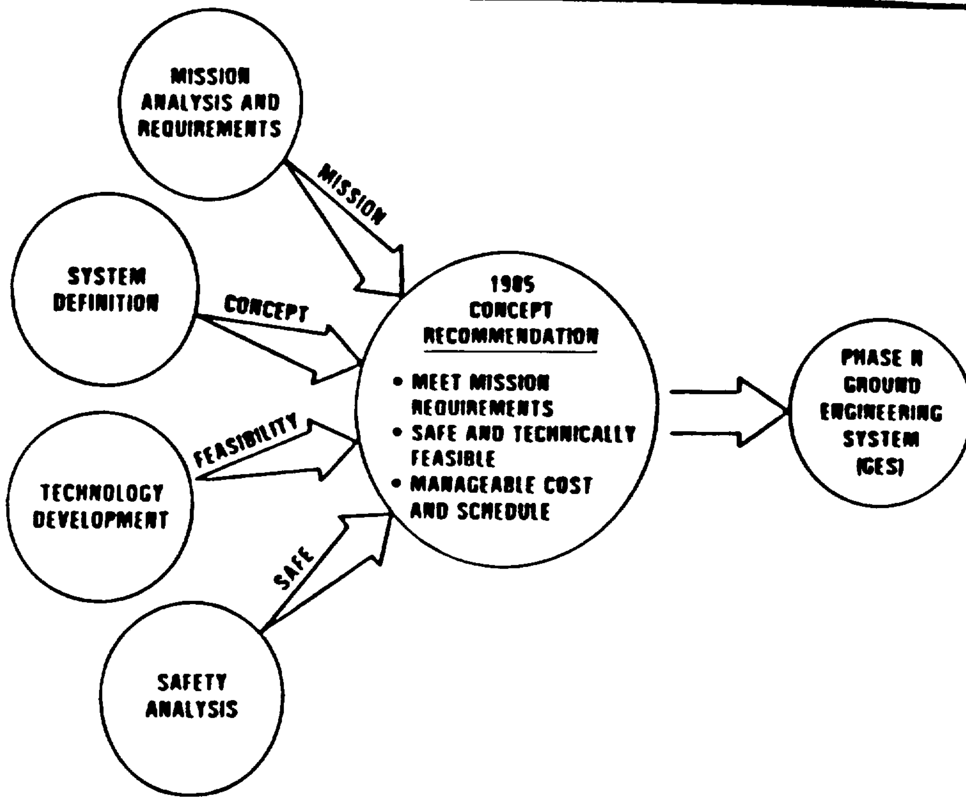
PHASE I - CONCEPT SELECTION - 1983

PHASE II - TECHNOLOGY DEVELOPMENT AND VALIDATION

PHASE III - FLIGHT DEMONSTRATION (F S 9)

RJS-910.04 5

SP-100
PHASE I PROGRAM



NASA

SP-100 PHASE I

- 50 ORIGINAL CONCEPTS
- 4 FINAL CONTENDERS
  - LIQUID METAL COOLED REACTOR (LMR)
    - THERMOELECTRICS
    - BRAYTON
    - STIRLING
  - IN-CORE THERMIONICS SYSTEM

RJS91-003.3

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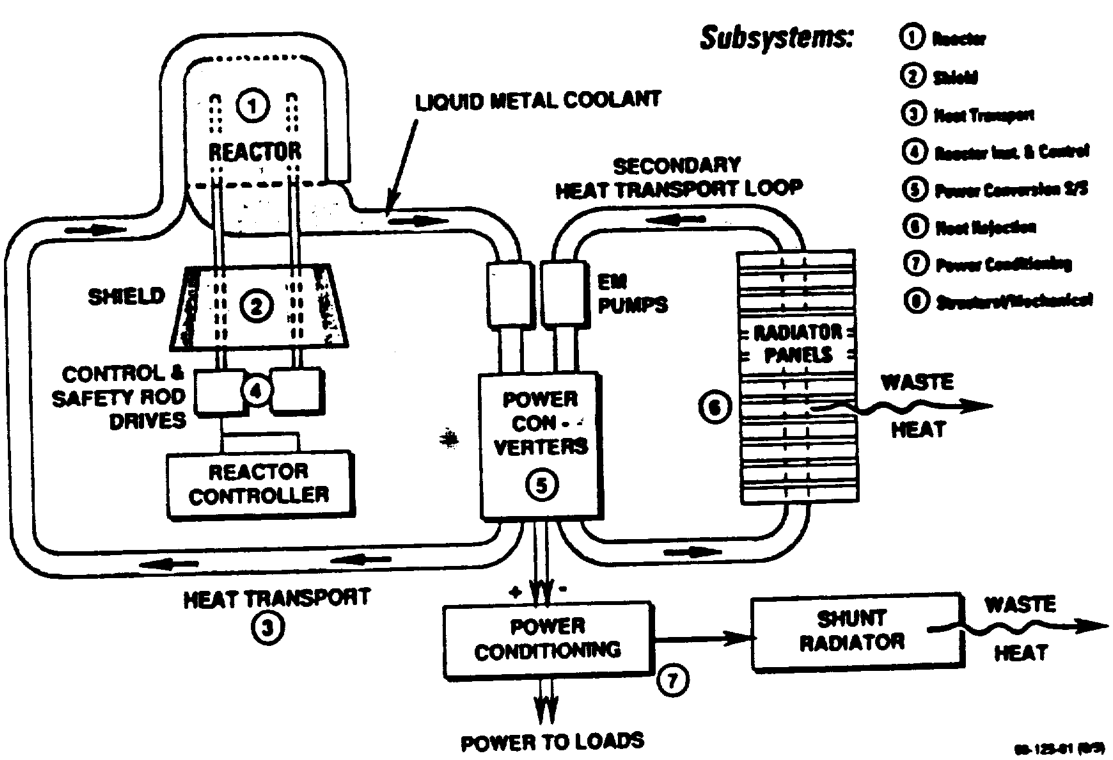
AT END OF PHASE I

- SP-100 GROUND ENGINEERING SYSTEM
  - LITHIUM COOLED REACTOR
  - TE CONVERSION
    - UN FUEL PWC-11 CLAD
    - 300 kWe ⟶ 100 kWe

- ADVANCED TECHNOLOGY PROGRAM (CSTI - HIGH CAPACITY POWER)
  - ADVANCED STATIC CONVERSION
  - DYNAMIC CONVERSION
  - RADIATORS
    - GROWTH
    - FALLBACK POSITIONS

- THERMIONICS TECHNOLOGY PROGRAM
  - ADDRESS UNRESOLVED FEASIBILITY ISSUES

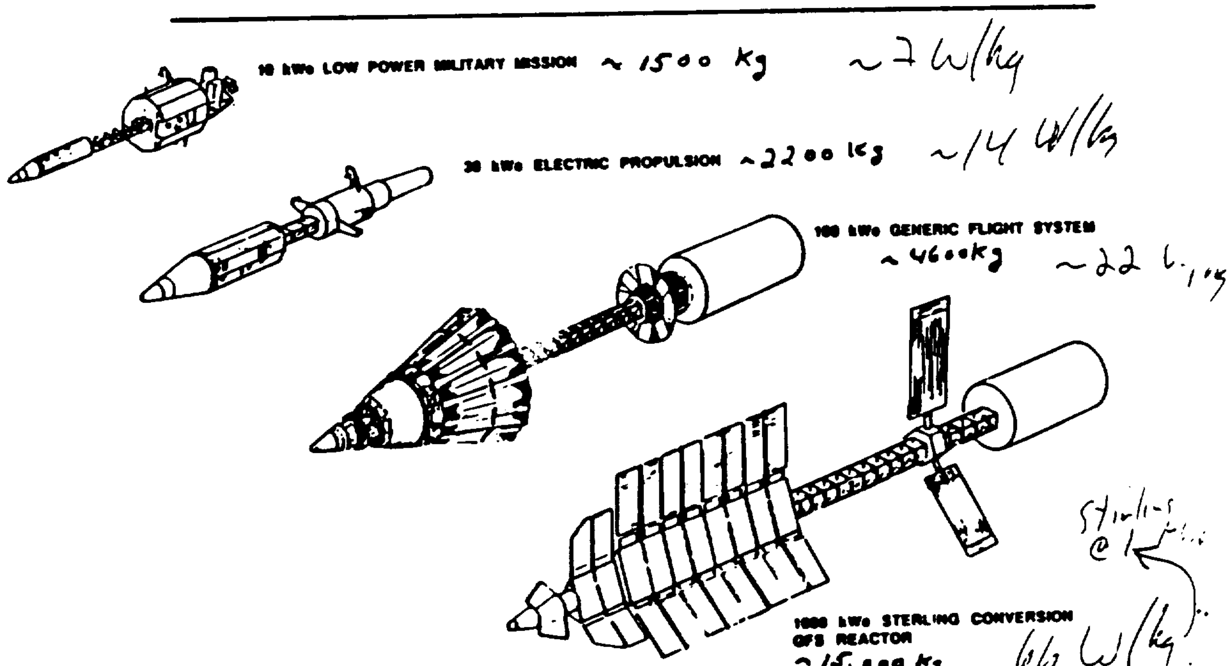
Simplified System Diagram



SCALING

ITP.RJS91-002.7

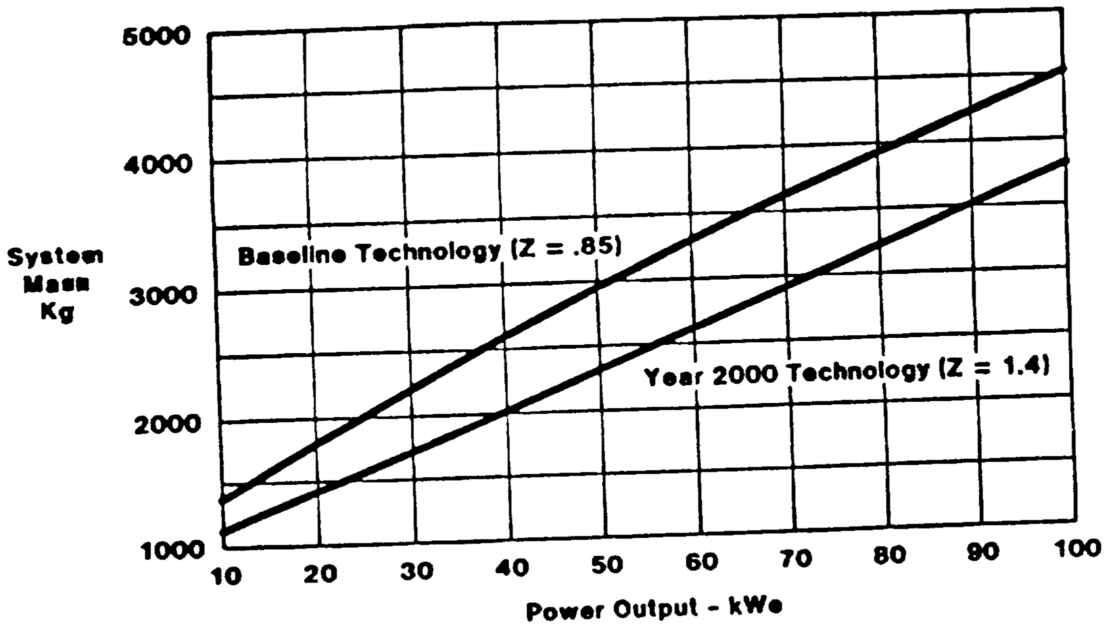
Design Scalability



SP-100 Technologies Applicable Over Wide Power Range

89-586-27

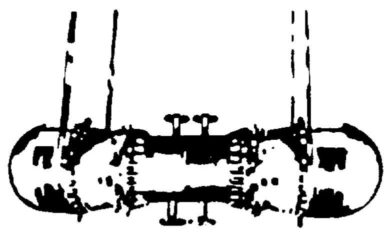
MASS SENSITIVITY TO T/E TECHNOLOGY STATUS

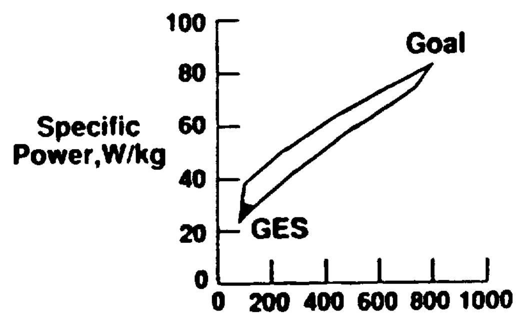


POWER TECHNOLOGY DIVISION

SPACE NUCLEAR POWER

High Capacity Power

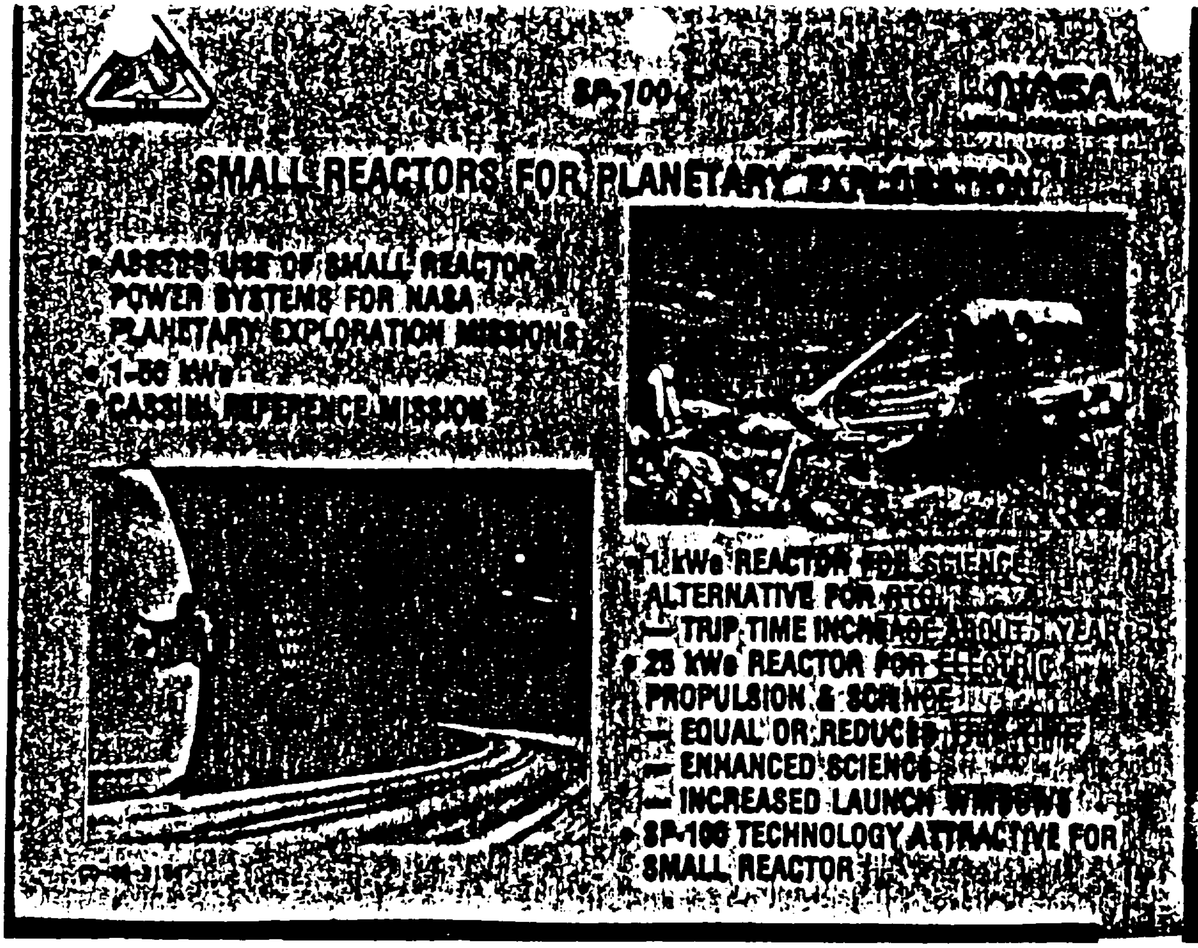


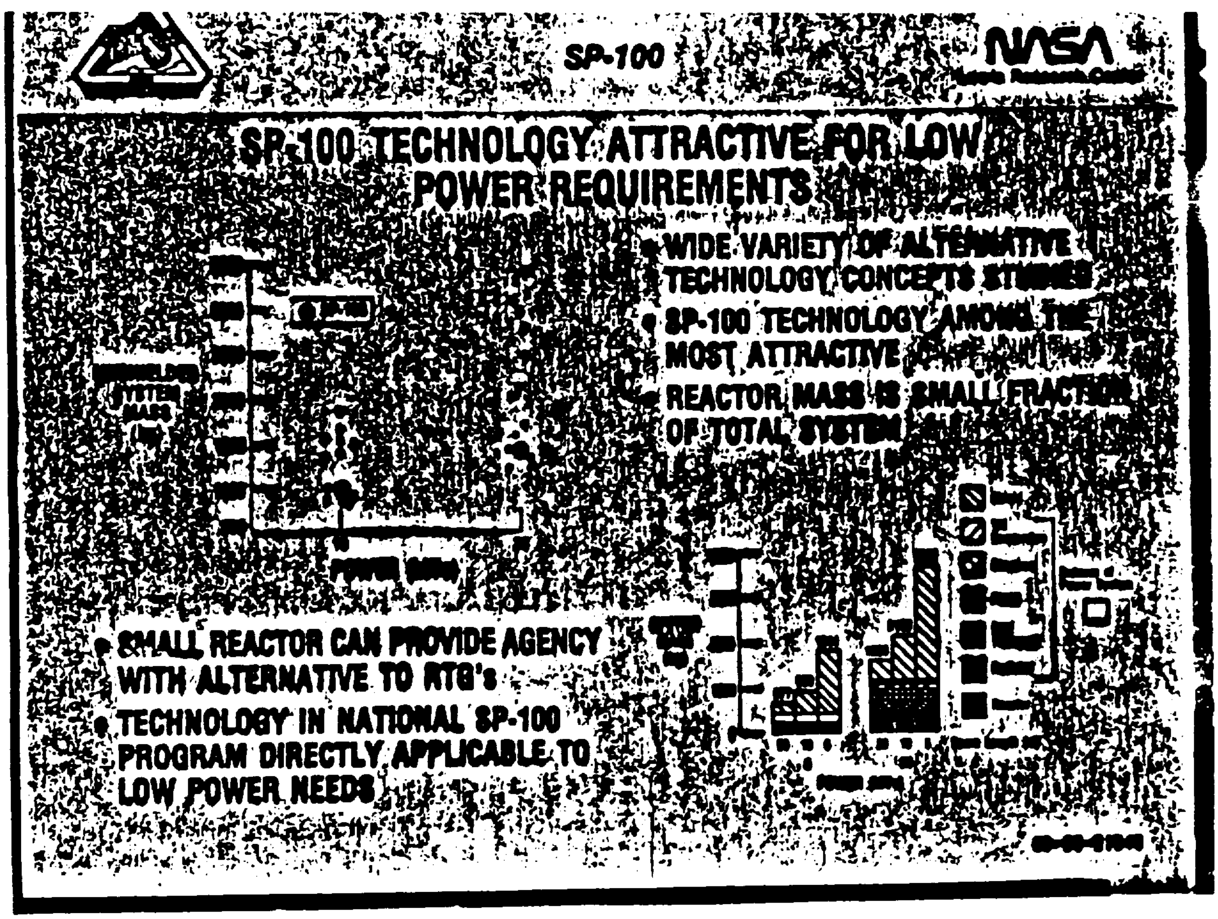


- Free piston Stirling converters
- Advanced thermal management
- Power management & distribution
- Environmental interactions
- Thermoelectrics
- Materials development

CD-88-40881

AEROSPACE TECHNOLOGY DIRECTORATE


SP-100
NASA
SMALL REACTORS FOR PLANETARY
• ASSESS USE OF SMALL REACTOR POWER SYSTEMS FOR NASA PLANETARY EXPLORATION MISSIONS
• CASSINI REFERENCE MISSION
• 1 kWe REACTOR FOR SCIENCE
ALTERNATIVE FOR RTG's
— TRIP TIME INCREASE
• 25 kWe REACTOR FOR ELECTRIC PROPULSION & SCIENCE
— EQUAL OR REDUCED TRIP TIME
— ENHANCED SCIENCE
— INCREASED LAUNCH WINDOWS
• SP-100 TECHNOLOGY ATTRACTIVE FOR SMALL REACTOR


SP-100
NASA
SP-100 TECHNOLOGY ATTRACTIVE FOR LOW POWER REQUIREMENTS
• WIDE VARIETY OF ALTERNATIVE TECHNOLOGY CONCEPTS STUDIED
• SP-100 TECHNOLOGY AMONG THE MOST ATTRACTIVE
• REACTOR MASS IS SMALL FRACTION OF TOTAL SYSTEM
• SMALL REACTOR CAN PROVIDE AGENCY WITH ALTERNATIVE TO RTG's
• TECHNOLOGY IN NATIONAL SP-100 PROGRAM DIRECTLY APPLICABLE TO LOW POWER NEEDS

NASA

SP-100 APPLICABILITY TO LARGE SCALE NEP 5 - 50 MWe

RJS91-003.11

NASA

MAJOR PARAMETERS CONSIDERED AND APPROACH USED

POWER RANGE CONSIDERED:	200 kWt TO 200 MWt
REACTOR LIFETIME:	10 YEAR BASELINE; LONGER LIFETIMES ARE FEASIBLE
FUEL/BURNUP:	UN / ≤ 10 ATOM %
COOLANT:	LITHIUM OR OTHER LIQUID METAL FOR PRIMARY HEAT TRANSPORT; - 1350K SECONDARY LOOP CAN BE LIQUID METAL, GAS, HEAT PIPES OR TBD
STRUCTURES:	REFRACTORY METAL; CAN USE HIGH TEMPERATURE ALLOYS SUCH AS 617 DEPENDING ON MISSION AND EXTERNAL ATMOSPHERE

RJS91-003.8

COROPT-S CODE CAPABILITIES

- o SP-100 NUCLEAR SUBSYSTEMS OPTIMIZATION CODE
- o USES FIRST PRINCIPLES TO SIZE REACTOR, SHIELD, PRIMARY HEAT TRANSPORT SYSTEM AND REACTOR I&C SUBSYSTEMS
- o DEMONSTRATED CAPABILITY TO SCALE SP-100 CONCEPT FOR A WIDE RANGE OF REQUIREMENTS AND CONCEPTS

TYPICAL OPTIMIZED PARAMETERS	CONSTRAINTS
CORE HEIGHT	PEAK BURNUP
PIN DIAMETER	F.G. PRESSURE STRAIN
PIN P/D RATIO	FCMI+FG PRESSURE STRAIN
CLADDING THICKNESS	MAX FUEL TEMP
PLENUM LENGTH	REACTOR ΔP
REFLECTOR THICKNESS	REFLECTOR WORTH
FUEL PELLET/CLADDING GAP	

- o SIZES AND PROVIDES MASS ESTIMATES IN SENSITIVITY OR OPTIMIZATION MODE

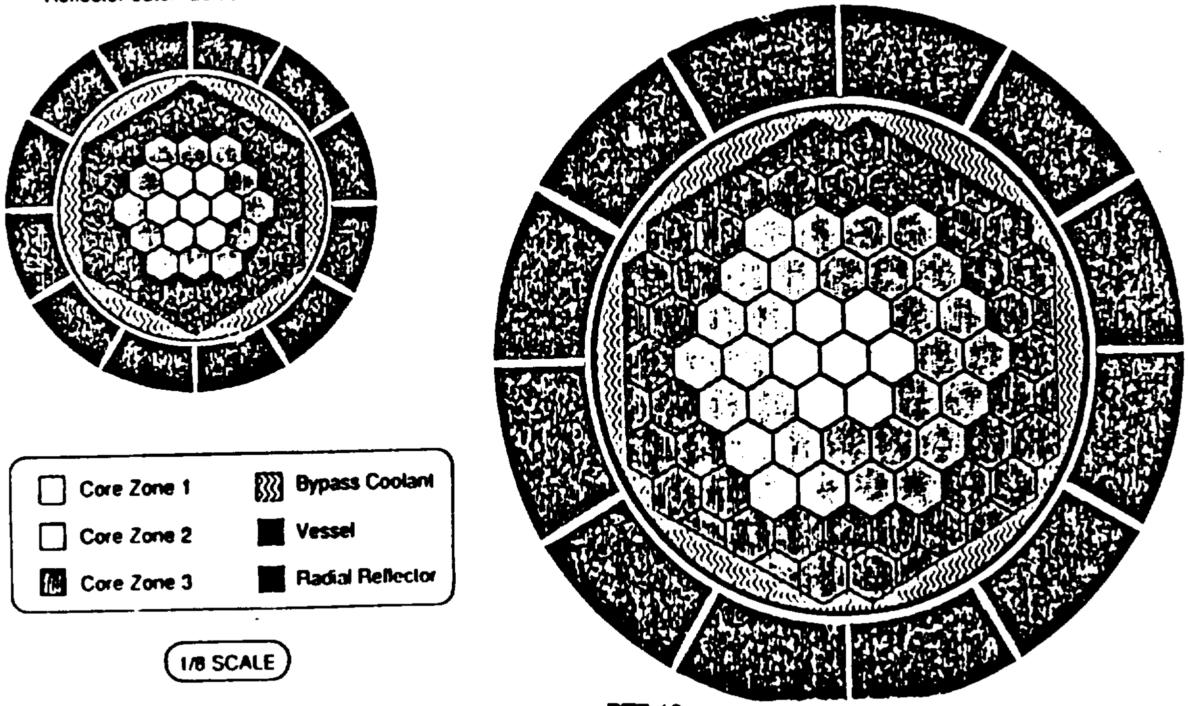
CORE CROSS SECTION SCHEMATIC

10MW

Number of full assemblies = 43
Number of partial assemblies = 12
Assembly pitch = 5.18 cm
Vessel outer radius = 21.6 cm
Reflector outer radius = 29.4 cm

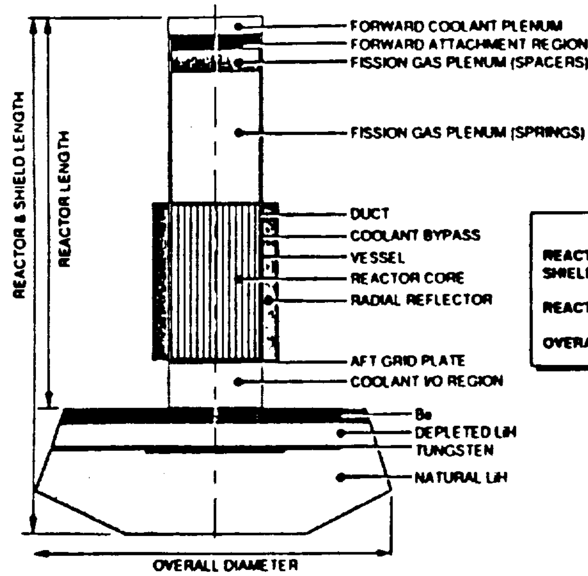
50MW

Number of full assemblies = 73
Number of partial assemblies = 12
Assembly pitch = 8.09 cm
Vessel outer radius = 40.9 cm
Reflector outer radius = 56.4 cm



REACTOR R-Z SCHEMATIC

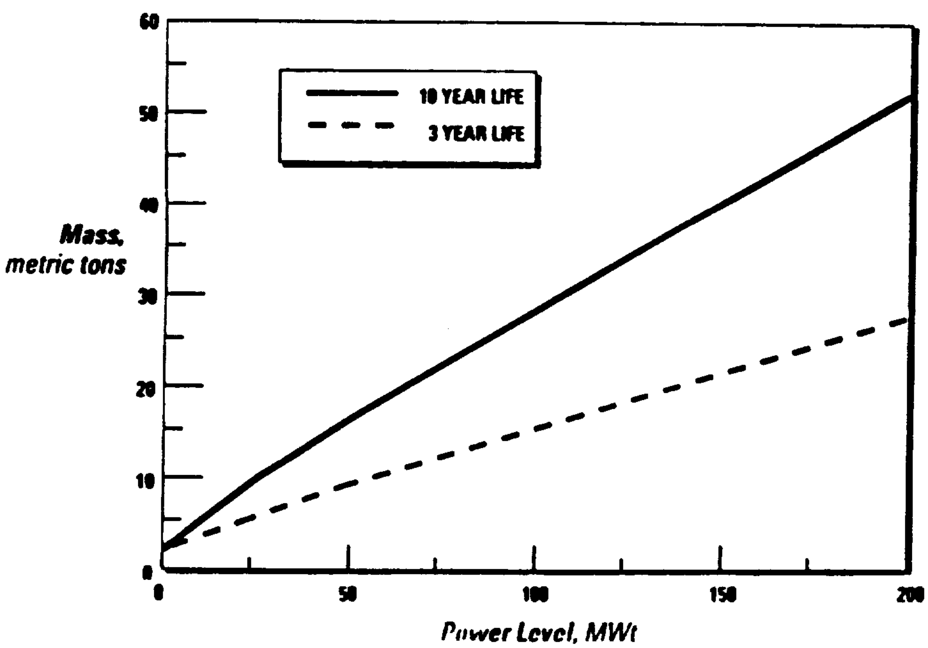
NASA



	25MW	50MW	200MW
REACTOR & SHIELD LENGTH (CM)	254	310	442
REACTOR LENGTH (CM)	198	249	378
OVERALL DIAMETER (CM)	210	296	406

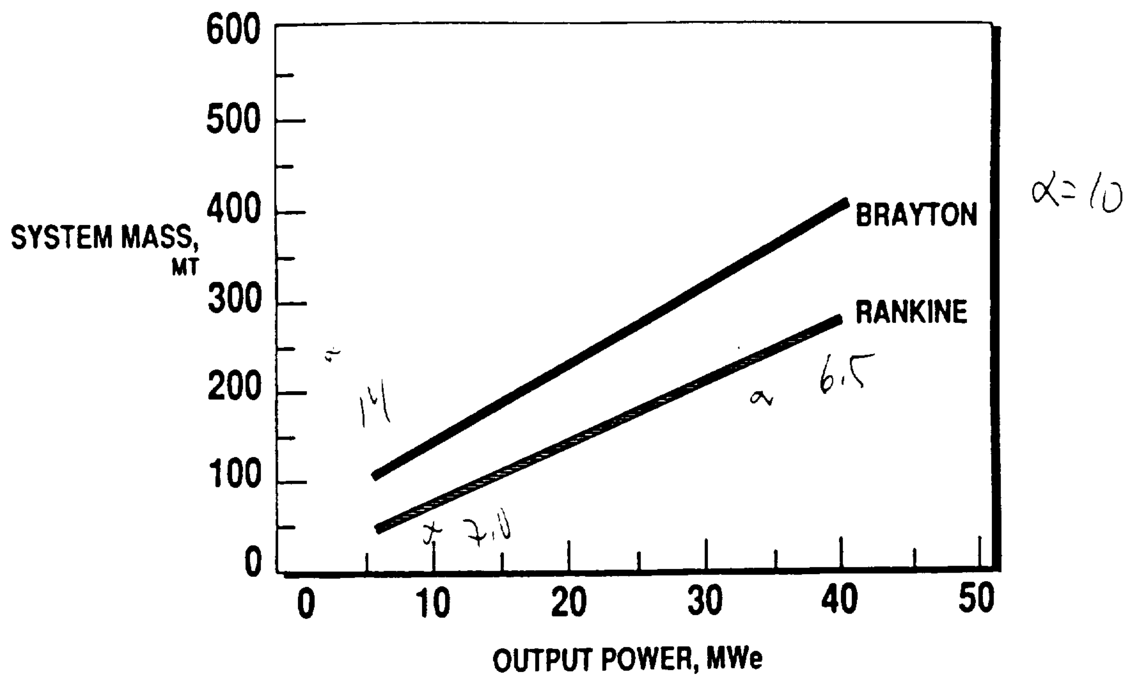
REACTOR SUBSYSTEM MASS vs LIFETIME

NASA



LeRC

SYSTEM MASS vs OUTPUT POWER



RJS-910 04 12

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DEVELOPMENT NEEDS

- o NO TECHNOLOGY DEVELOPMENT ITEMS BEYOND GES
- o KEY FEATURE TESTS NEEDED
  - CRITICAL EXPERIMENT
  - SLIDING REFLECTOR
  - SCALED-UP CONTROL DRIVE
  - SCALED-UP PUMP
  - FLOW TEST
  - Li^7H NUCLEAR HEATING TEST
  - EXTEND FUEL AND MATERIALS IRRADIATION DATA BASE

NASA

SDIO IEG STUDY

- SP-100 TECHNOLOGY FOR MMWe APPLICATIONS
- CHANGE CLAD ⟶ INCREASE TEMPERATURE 1600 K
- PERFORMANCE EQUIVALENT TO PROPOSED LMC REACTOR SPECIFICALLY PROPOSED FOR ADVANCED CONVERSION

EXPLORATION TECHNOLO

SP-100 GROUND ENGINEERING

SYSTEM STORY

ITP.RJS91-002.8

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SP-100 GES PROJECT

PHASE II PROGRAM OBJECTIVE

- DEVELOP AND DEMONSTRATE BY 1992 THAT THE TECHNOLOGY IS READY FOR FLIGHT APPLICATION OF 10 TO 1000 kWe SPACE REACTOR POWER SYSTEMS FOR FUTURE MILITARY AND CIVILIAN SPACE MISSIONS.

THE SP-100 GES PROGRAM

LeRC

OBJECTIVE

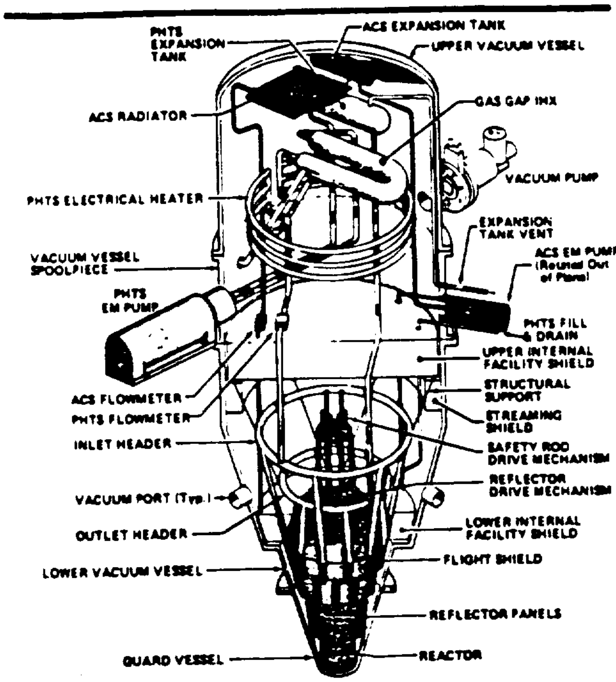
- CONDUCT THE ENGINEERING DEVELOPMENT AND GROUND SYSTEM TESTING OF A REACTOR SPACE POWER SYSTEM FOR POWER LEVELS OVER THE RANGE OF 10's TO 100's OF KILOWATTS ELECTRIC.

SCOPE

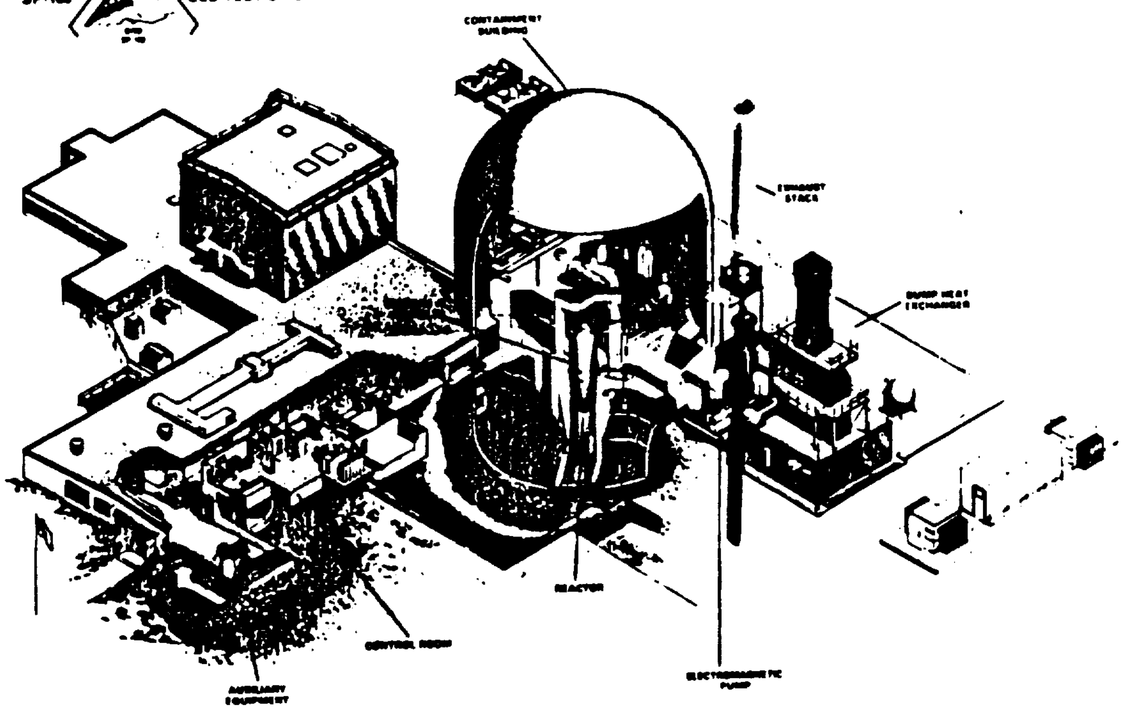
- SUBSYSTEM TECHNOLOGY OF THE COMPLETE POWER SYSTEM (DEMONSTRATE COMPONENT LIFETIME)
  - REACTOR AND SHIELD
  - THERMOELECTRIC POWER CONVERTER
  - HEAT TRANSPORT
  - HEAT REJECTION
  - INSTRUMENTATION AND CONTROL
  - POWER CONDITIONING, CONTROL, AND DISTRIBUTION
  - STRUCTURAL
- TWO MAJOR PERFORMANCE TESTS (DEMONSTRATION SYSTEM PERFORMANCE)
  - NUCLEAR ASSEMBLY TEST (NAT)
  - INTEGRATED ASSEMBLY TEST (IAT)
- SYSTEM EFFORTS
  - MANAGEMENT
  - SYSTEM DESIGN
  - RELIABILITY AND QUALITY ASSURANCE
  - SAFETY
  - SYSTEM STUDIES (SCALEABILITY, MAINTAINABILITY)

RJS-910 04 15

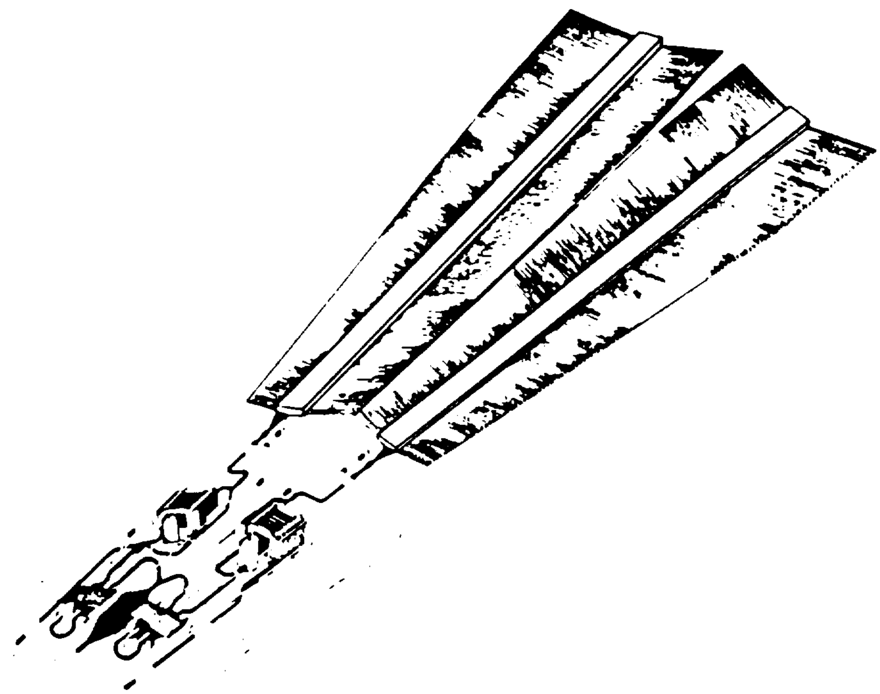
Test Assembly

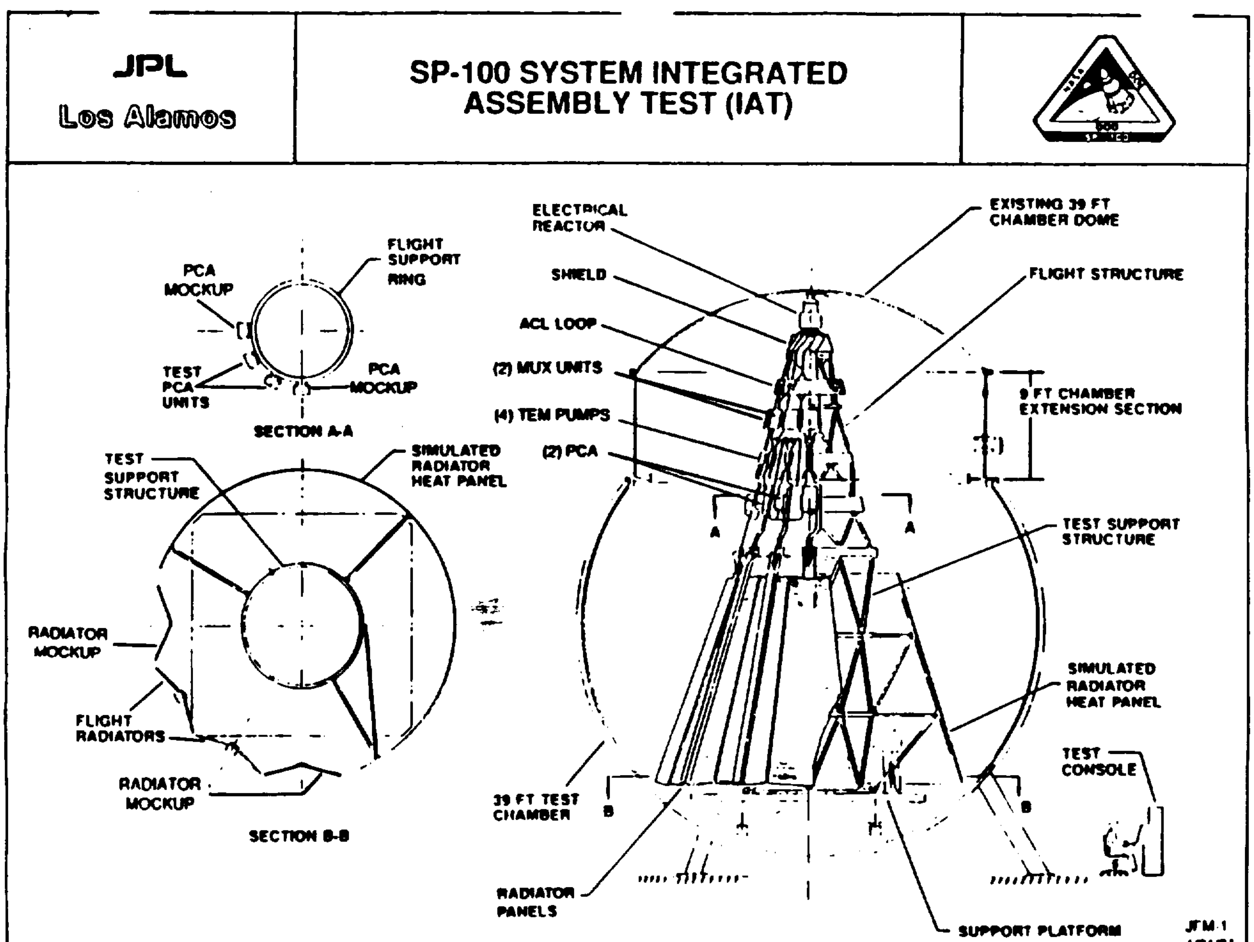


SP-100 GES TEST SITE



ENERGY CONVERSION ASSEMBLY SEGMENT





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BASELINE COSTS (M$)

FY	87	88	89	90	91	TOTAL
	122	153	148	115	77	641

- PROGRAM SCOPE/SCHEDULE ADJUSTMENTS HAVE BEEN REQUIRED AS RESULT OF CONTINUED BUDGET SHORTFALLS

GENERALLY - STRETCH NAT
- STRETCH/ELIMINATE SPACE SUBSYSTEMS EFFORTS
- INCREASE OVERALL BUDGET

FY	87	88	89	90	91
PLANNED	80	160	165	107	91
ACTUAL	64	94	77	78	50

	92	93	94
RUNOUT	103	112	117

RJS-91Q 04 16

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SP-100

PROGRAM REVIEW GROUP

1989 - 90

RJS-91Q 04 18

SP-100 PROGRAM REVIEW GROUP PRESENTATION

NASA

June 15, 1990

SP-100 PROGRAM REVIEW GROUP FINDINGS

- **There is a clear need for Space Reactor Power**
  - Enabling for NASA Space Exploration Initiative (earliest projected NASA application)
  - Enhancing for SDIO and USAF mission (USAF evaluating future role of space reactor power)
- **Top level SP-100 requirements are still appropriate**
  - Power range (10's to 100's kWe)
  - Lifetime (7 years full power)
- **Decision to select thermoelectric conversion still appropriate**

SP-100 PROGRAM REVIEW GROUP FINDINGS

(continued)

- **Significant progress has been made by the SP-100 Program**
  - Hardware being fabricated
  - Major advancements in thermoelectrics and fuel rod construction
  - Technical areas of concern in reactor and converter being addressed
  - Funding shortfalls are the principal threat to balanced technical progress

SP-100 PROGRAM REVIEW GROUP FINDINGS

(continued)

- **There is a major deficiency in the current program**
  - Development effort is limited to reactor and converter
  - Key overall system development not being addressed
  - Key technical areas in non-nuclear space subsystems not being addressed (e.g., heat rejection)

1991 REDIRECTED FLIGHT SYSTEM QUALIFICATION

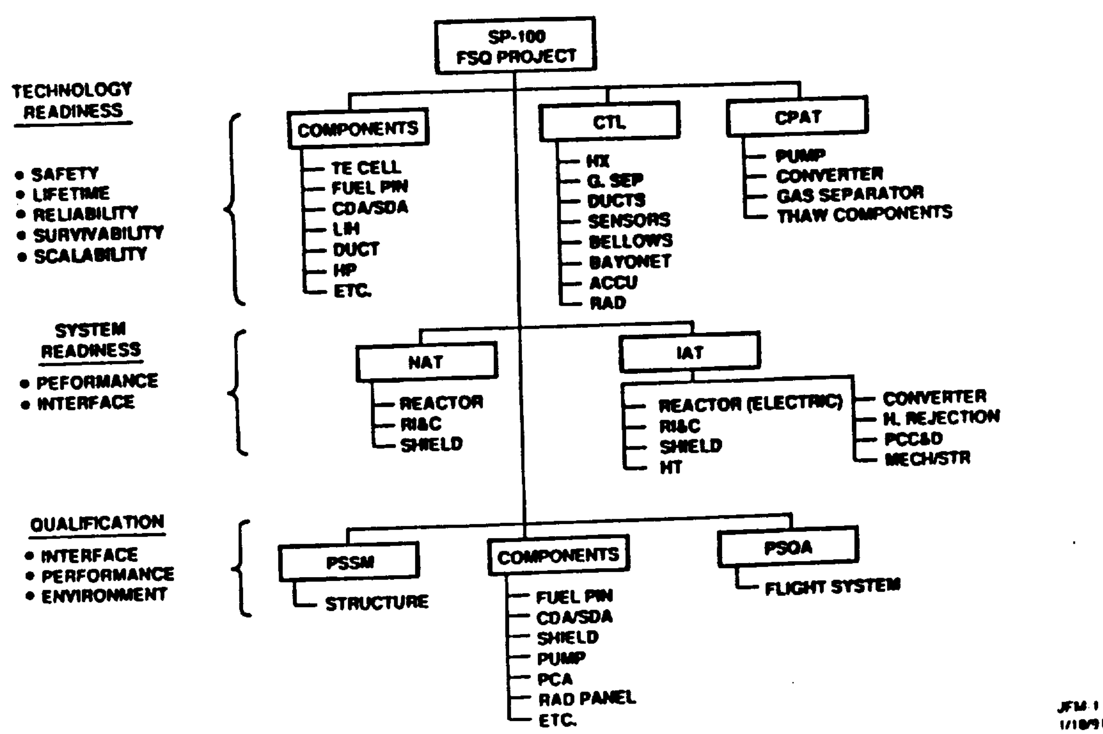
- RE-ORIENT TO COMPONENT DEVELOPMENT FOCUS
- DELAY NAT
- DEMONSTRATE EARLY COMPLETION OF NUCLEAR AND SPACE TECHNOLOGY READINESS - 98
- EARLY CONVERTER/PUMP ASSEMBLY TEST - 96
- REDESIGN OF NUCLEAR ASSEMBLY UPDATE
- LEAST SENSITIVE TO FUNDING DISRUPTIONS

FJS91-003.7

JPL

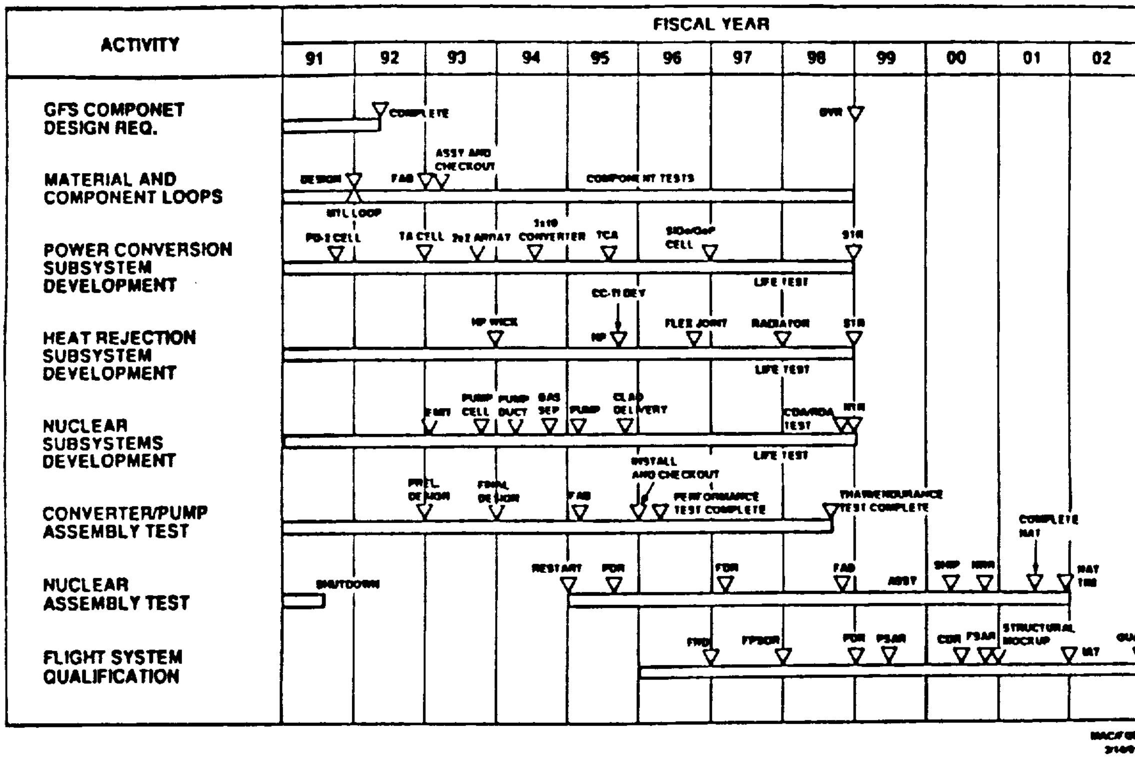
Los Alamos

SP-100 FLIGHT SYSTEM QUALIFICATION PROJECT APPROACH



JFM-1
1/18/91

SP-100 FLIGHT SYSTEM QUALIFICATION PROGRAM SUMMARY SCHEDULE



SP-100 GES PROGRAM STATUS & OPTIONS

LeRC

- **GES PROGRAM**
  - THRU FY90 $320M HAS BEEN SPENT -
    - ~ $240M FOR NUCLEAR SUBSYSTEM
    - ~ $ 80M FOR SPACE (NON-NUCLEAR) SUBSYSTEM

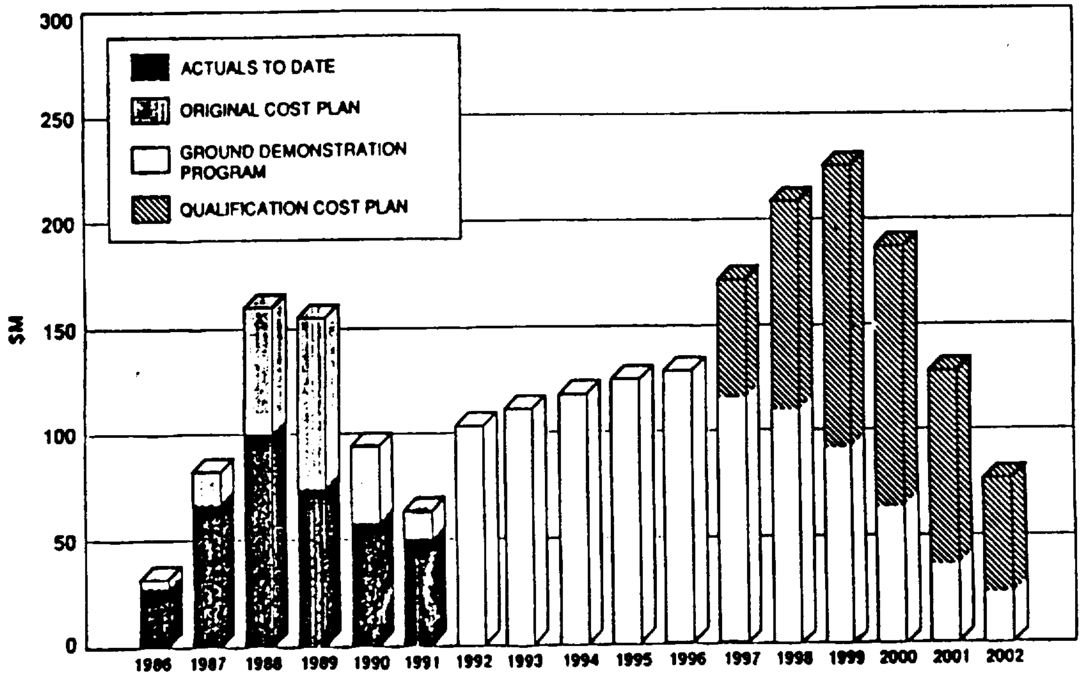
- **CURRENT FSQ PROGRAM**
  - WITH EXPECTED (PLANNED) ANNUAL FUNDING RATE A TRL 6
  - CAN BE ACHIEVED IN 2001 WITH TOTAL FUNDING OF $1284M THRU FY2001
    - $1064M FOR NUCLEAR SUBSYSTEM
    - $ 220M FOR SPACE (NON-NUCLEAR) SUBSYSTEM

- **OPTIONAL ACCELERATED PROGRAM**
  - CAN ACHIEVE A TRL 6 BY 1997 FOR $1145M

FY	92	93	94	95	96	97	TOTAL
REQ'D FUNDING RATE	125	170	225	235	220	170	1145
PLANNED FUNDING RATE	103	110	115	123	130	110	691
ADD'L FUNDING NEEDED	22	60	110	112	90	60	454

RJS-910 04 24

FSQ PROGRAM COST



Spent to date $320 M 240 80 space

ATM-4
2/19/91

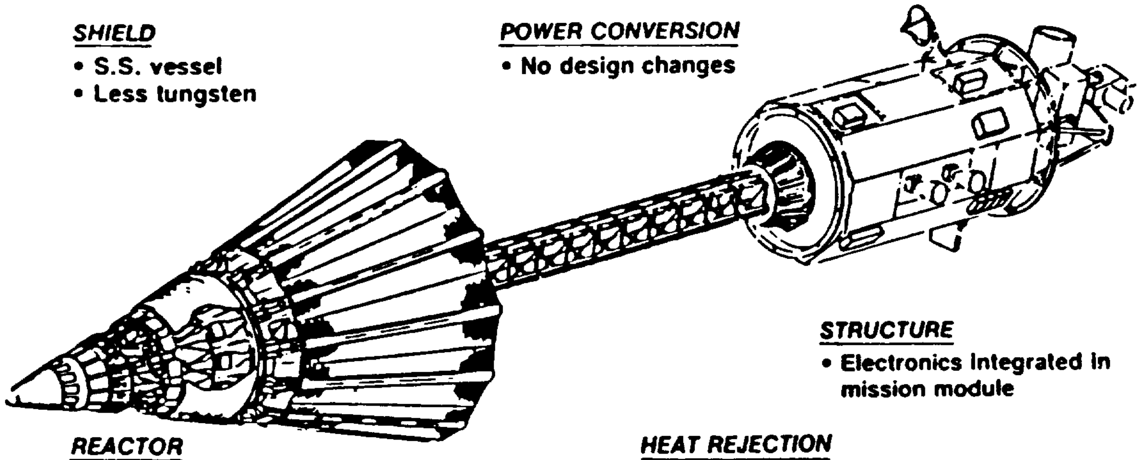
EXPLORATION TECHNOLOGY

TECHNICAL PROGRESS

ITP.RJS91-001.4

GFS Design Options

New Features



NFS23

JPL

Los Alamos

FIVE CANDIDATE THAW SYSTEMS

- O AUXILIARY COOLANT LOOP/NaK TRACE LINE/SEQUENTIAL THAW (ACT)
- O AUXILIARY COOLANT LOOP/BLEED TUBE
- O BLEED TUBE THAW CONCEPT
- O HEAT PIPE THAW CONCEPT
- O SEQUENCED ELECTRICAL HEATER CONCEPT

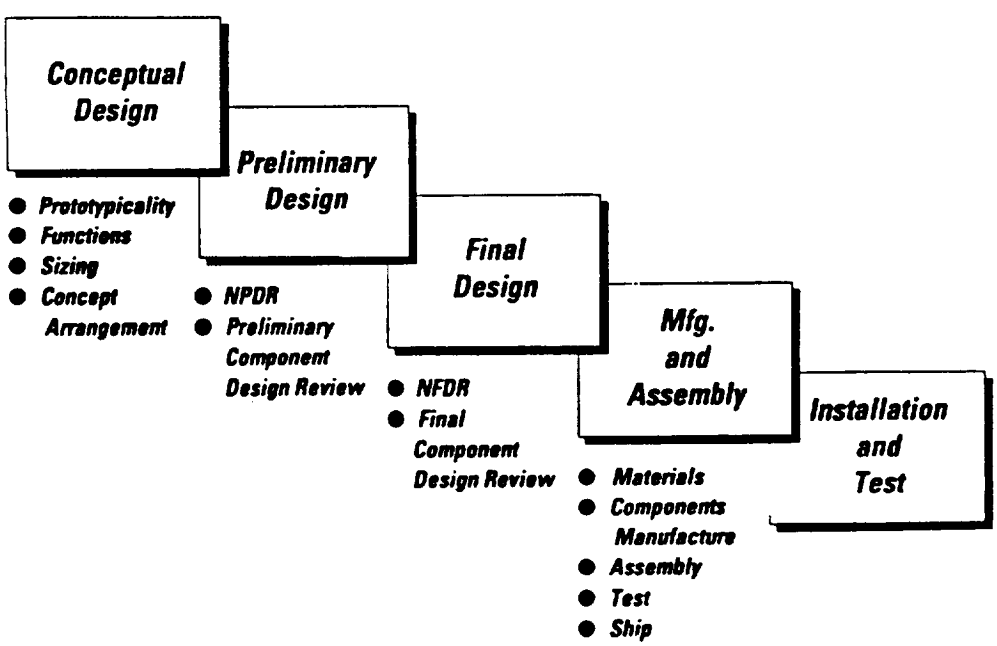
NASA

SP-100 GES PROGRESS

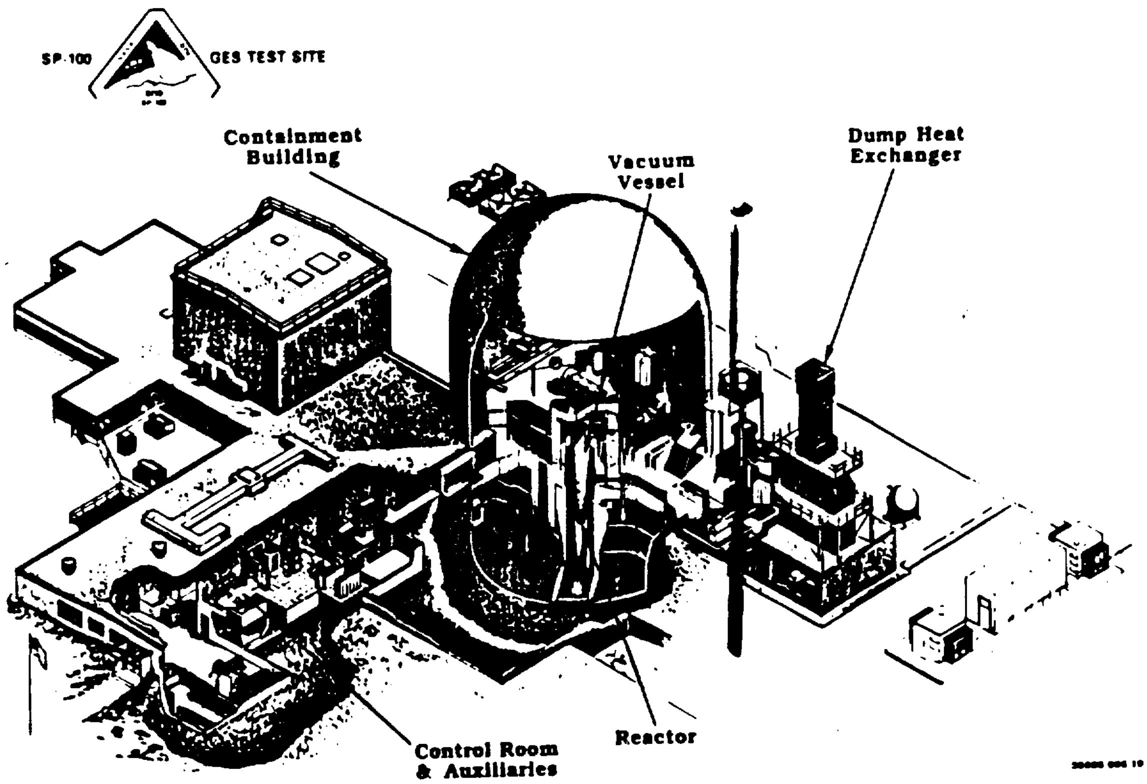
- GENERIC REFERENCE FLIGHT SYSTEM DESIGN
- SUBSYSTEM AND COMPONENT SPECIFICATIONS
- MATERIALS, PROCESS AND FABRICATION SPECIFICATIONS
- VALIDATION PLAN
- EIS, FONSI, ETC., FOR FACILITY

RJS91-003.14

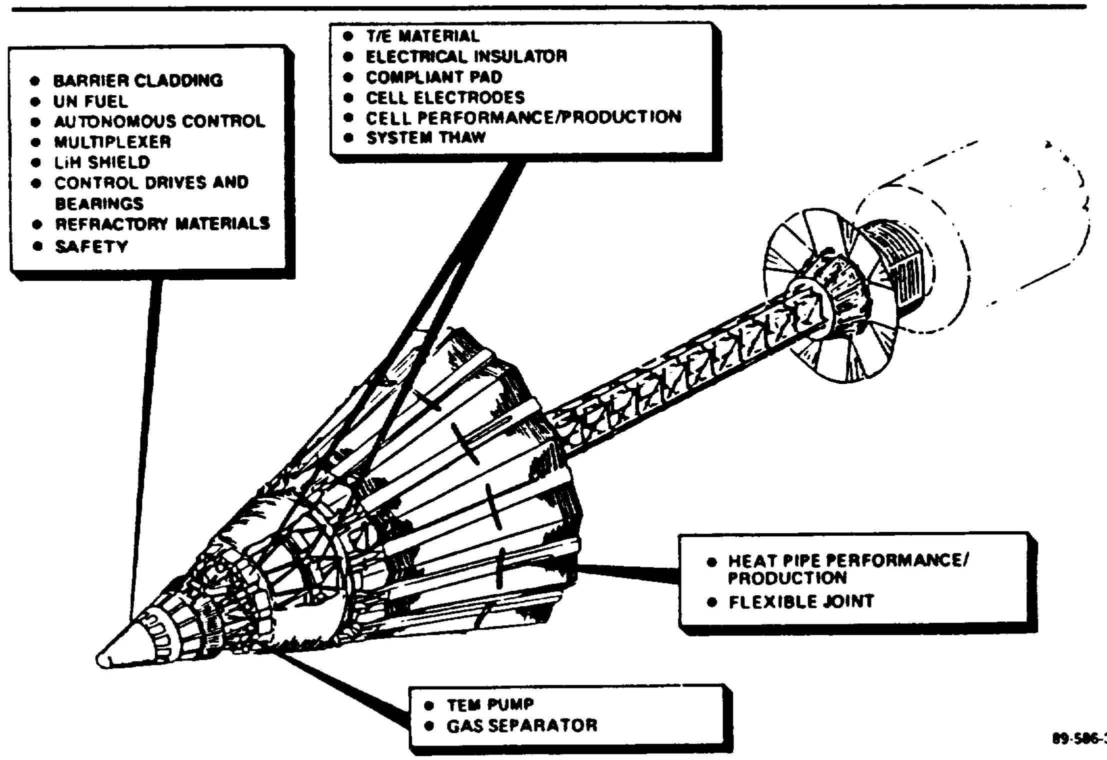
Nuclear Assembly Test Progress



NSS 086 90-520-35

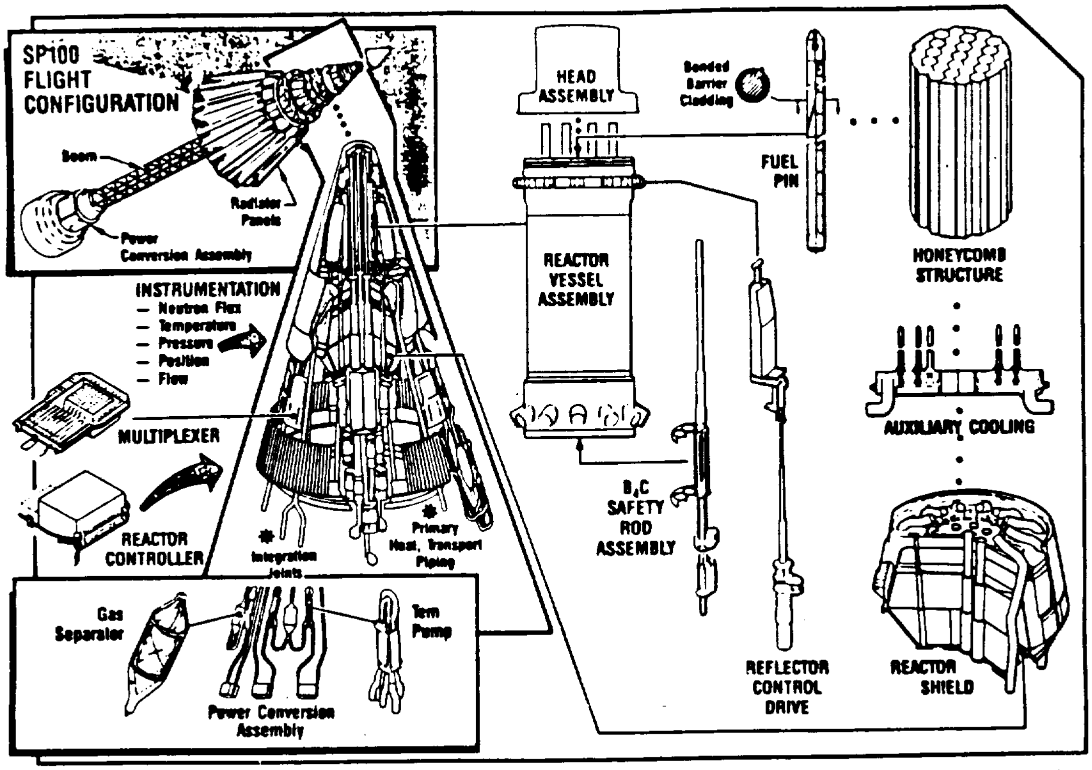


SP-100 Key Technologies



89-586-33

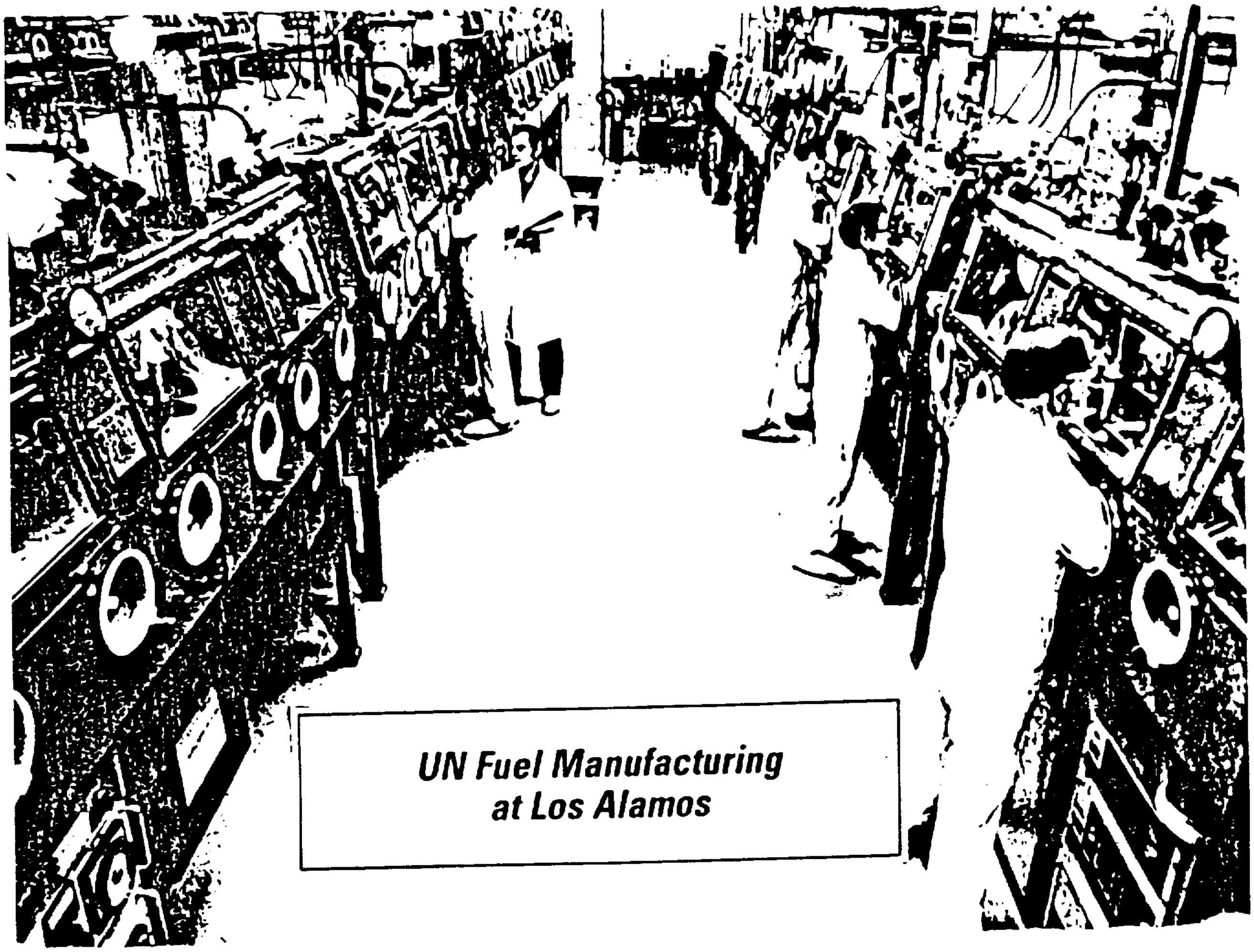
SP-100 GENERIC FLIGHT SYSTEM
NUCLEAR SUBSYSTEM KEY TECHNOLOGIES



SP-100 Uranium Nitride Fuel

- ***Process Developed at Los Alamos National Laboratory***
- ***Meets Exacting GE Specifications***
  - ***Chemistry***
  - ***Dimensions***
  - ***Density***
  - ***Microstructure***
  - ***Quality Assurance***
- ***Pellet Production for Nuclear Assembly Test Nearing Completion***

NSS 053 90-520-24



SP-100 Uranium Nitride Fuel

NSS 092 90-520-22

JPL
LOS ALAMOS

NAT FUEL PRODUCTION (LANL Status)

- Total NAT fuel pellets required

  49,000 - 97 % enriched

  ~ 6600 - 89 or 93 % enriched (depends on GFS updated design)

- Total NAT fuel pellets currently fabricated

  44,400 - 97 %

  zero - 89 or 93 % (93 % enrichment feedstock available)

- Total fuel pellets requiring resintering

  44,400 - 97 %

- Fuel pellets currently resintered

  9700 - 97 %

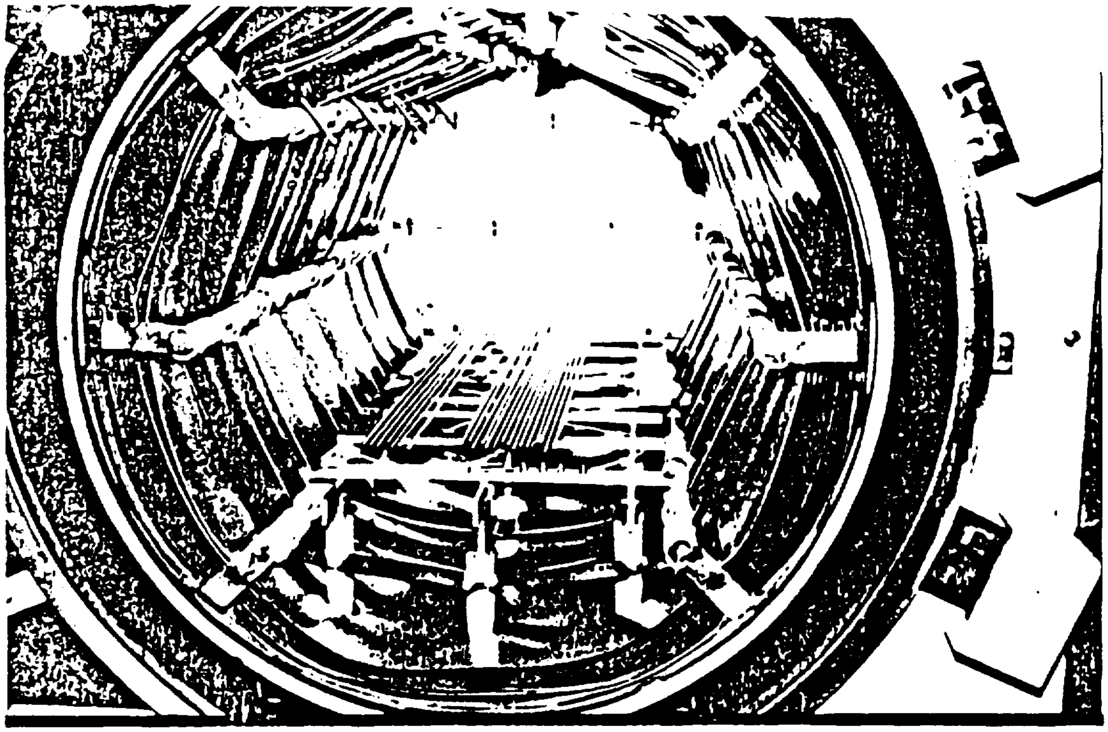
3/19/91

SP-100 Materials Technology

- *Demonstrated Fabricability of Re Lined Nb-1Zr (Barrier) Fuel Cladding*
- *Demonstrated High Creep Strength of Barrier Cladding*
- *Demonstrated Effectiveness of Chemistry Control and/or Heat Treatment in Preventing Li Attack of Nb-1Zr Welds*
- *Demonstrated High Temperature Strength of Controlled Chemistry Nb-1Zr*
- *Demonstrated Dynamic Friction Properties of ZrC and HfC Hardfacings Under High Temperature (1600 °K) High Vacuum (10^{-8} Torr) Conditions*

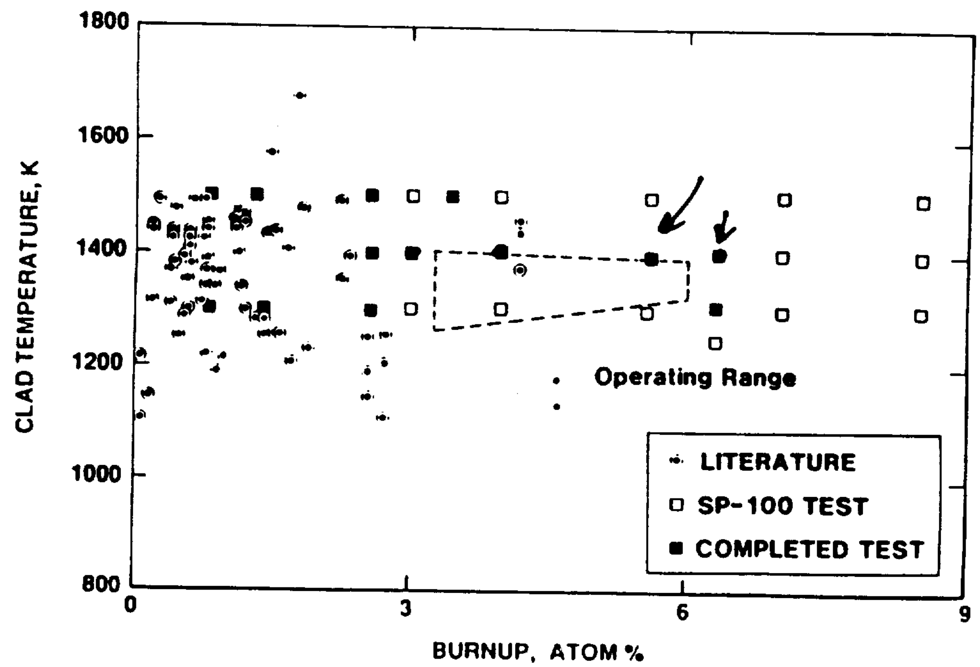
Mvm to PWC-11

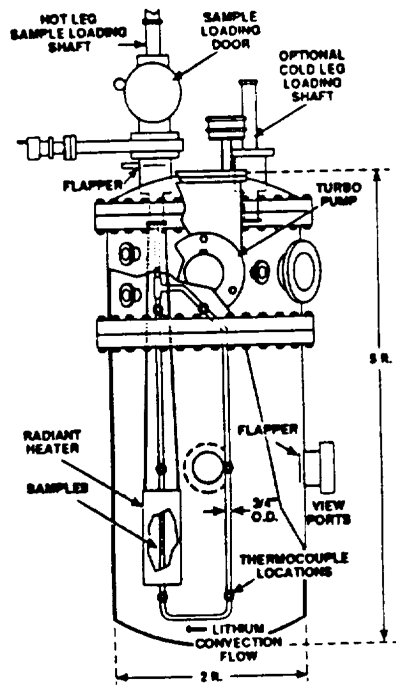
NSS 049 90-520-19



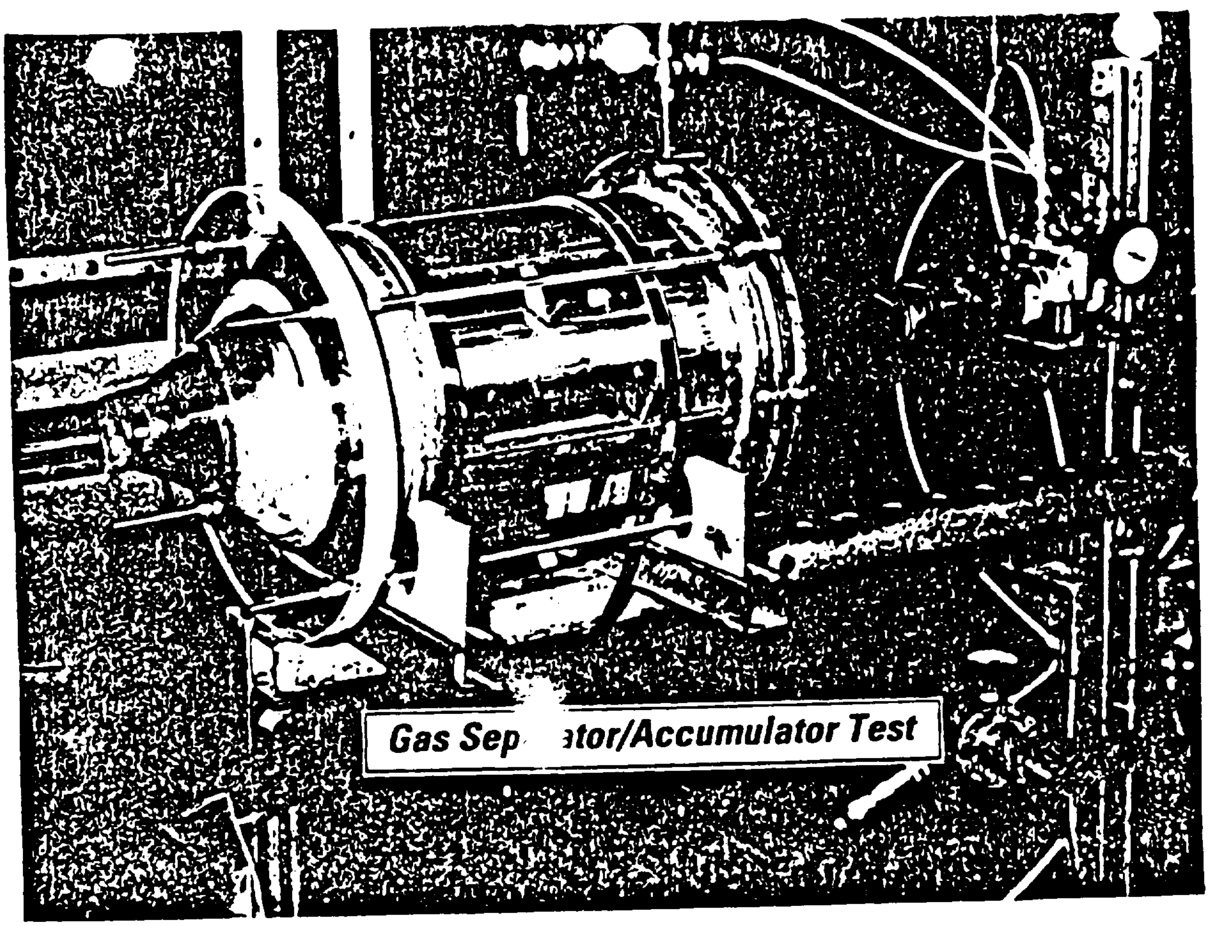
22 TUBES OF QUALIFICATION BATCH 1 IN THE VACUUM HEAT TREAT FURNACE AFTER BEING DRAWN TO FINAL SIZE

Fuel Pin Supporting Data





NSS 084 90-520-33

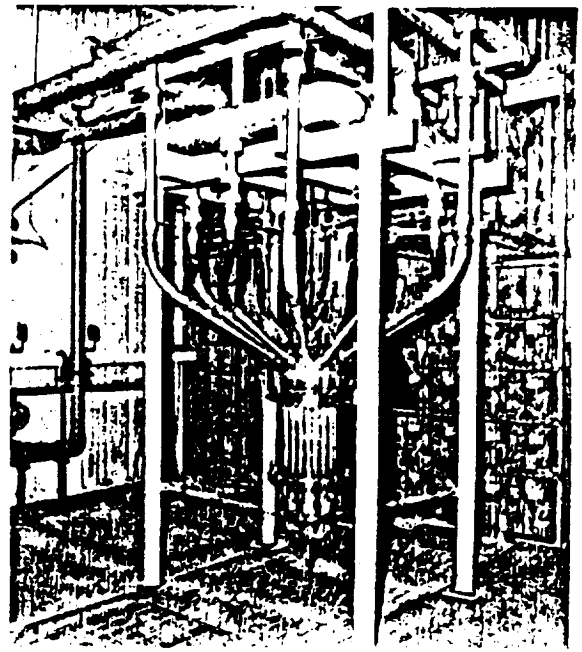


Gas Sep ator/Accumulator Test

ORIGINAL PAGE IS OF POOR QUALITY

SP-100 Full Scale Hydraulic Flow Test

- Measured Overall Pressure Drop
- Measured Coolant Flow Distribution Within Reactor Core
- Verified Orifice Sizing Predictions
- Investigated Reactor Hydraulic Characteristics:
  - Entrance to Annulus Losses
  - Annulus to Core Entrance Losses
  - Exit Plenum to Reactor Outlet Losses
  - EfFects of Inlet Pipe Blockage on Coolant Distribution
- Tests Complete



NSS 053 90-520-23

Control Drive Development

Key Feature Test
- SRDA SCRAM Shutdown
- RCDA Operation and SCRAM
- Safety Rod Separation Joint

Component Tests
- Electromagnetic Coils
- Actuator Bearings
- Motor, Clutch Brake and Position Sensor
- Spherical Self-Align. Bearings
- Safety Rod Slider Bearings

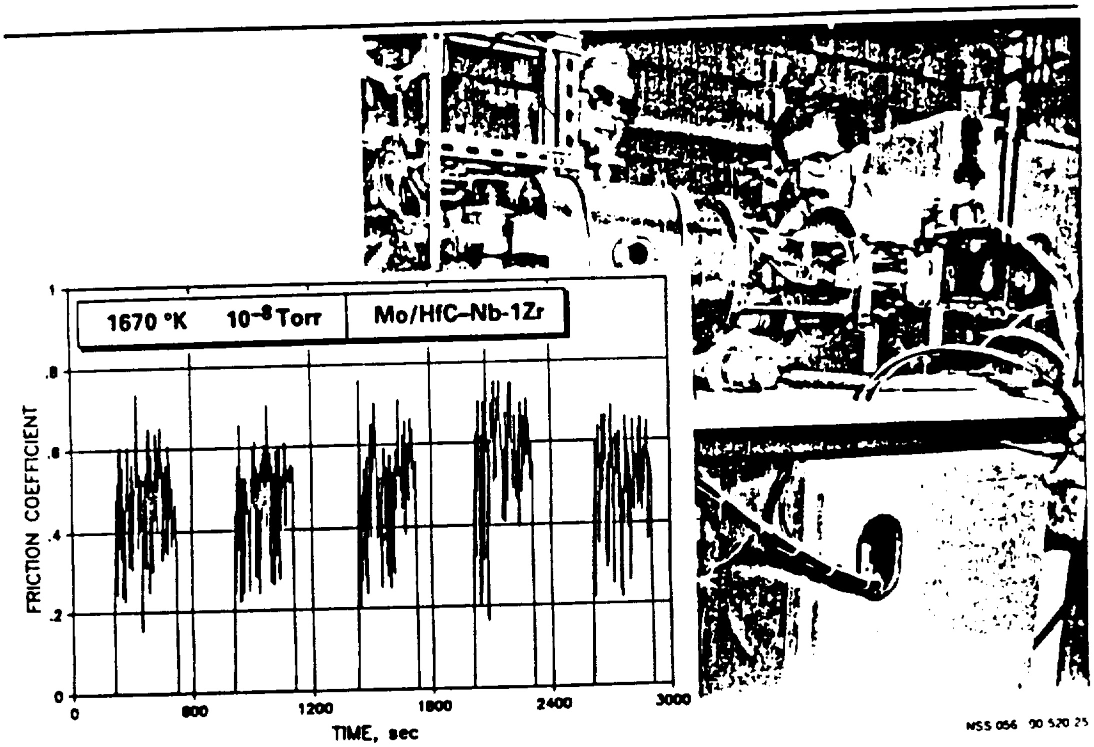
Sub-assembly Test
- Drive Motor
- Drive Actuator
- Hinged Reflector
- Safety Rod Driveline

Prototype Tests
- SRDA (2)
- RCDA (2)

Endurance Tests
- SRDA (2)
- RCDA (2)

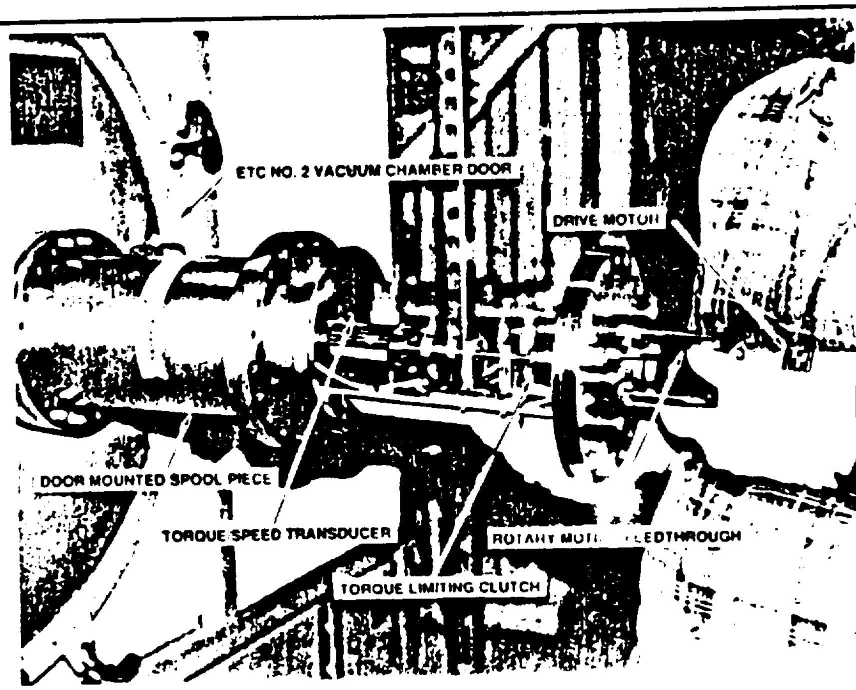
NSS 070 90-520-39

High Temperature Tribology



NSS 056 90 520 25

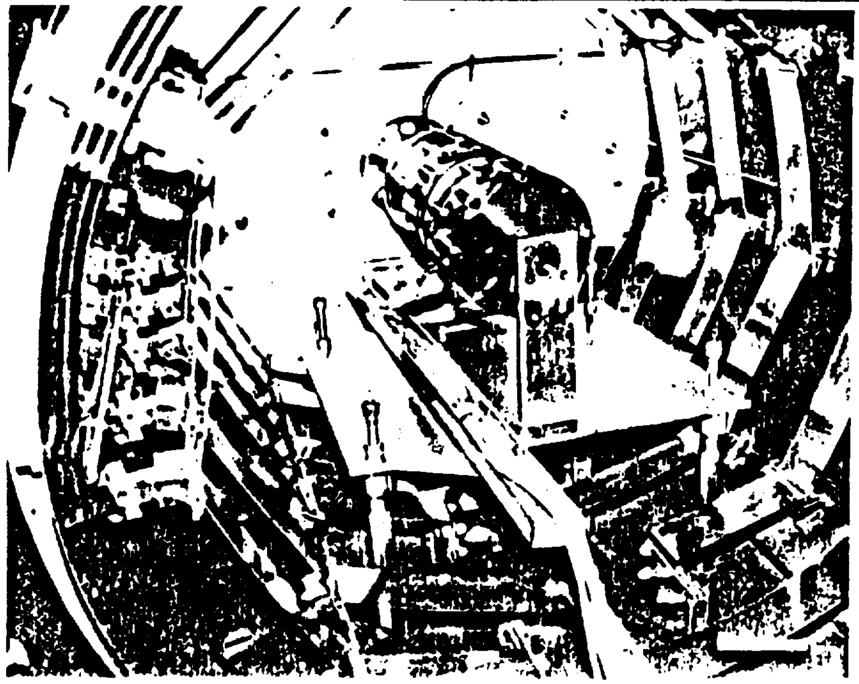
Control Drive Self-Aligning Bearing Test



NSS 057 90 520 26

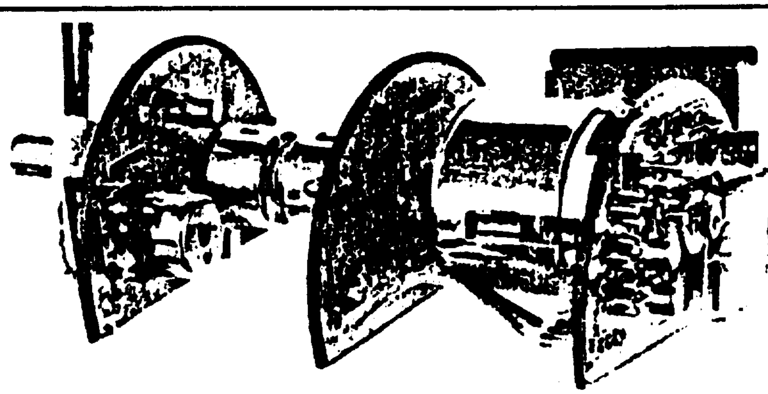
OF POOR QUALITY

Control Drive Clutch/Resolver Test



NSS 058 90-520-27

Multiplexer Development



Gamma:
- No JFET Damage
- 50°C
- Dose Acceleration 15:1

Neutron:
- 40% JFET Damage
- 50°C
- Dose Acceleration 120:1

Acceptable Performance Expected at Lower Dose Rates & Higher Temperatures

NSS 063 90-520-32

JPL

Los Alamos

SPACE SUBSYSTEM TECHNICAL CHALLENGES

HEAT TRANSPORT SUBSYSTEM
- TE-EM PUMP MASS AND EFFICIENCY
- TEM PUMP TE CELL

POWER CONVERSION SUBSYSTEM
- HIGH VOLTAGE INSULATOR
- COMPLIANT PAD
- ELECTRODES
- TE CELL ASSEMBLY
- IMPROVED SiGE

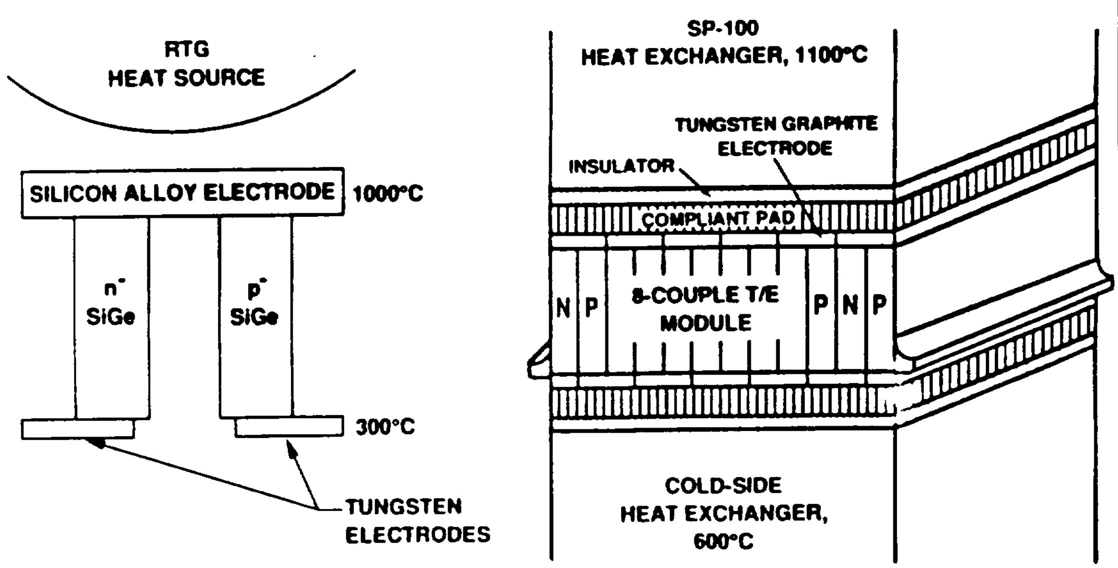
HEAT REJECTION SUBSYSTEM
- HEAT PIPE
- RADIATOR DUCT THAW

JM 33

JPL

Los Alamos

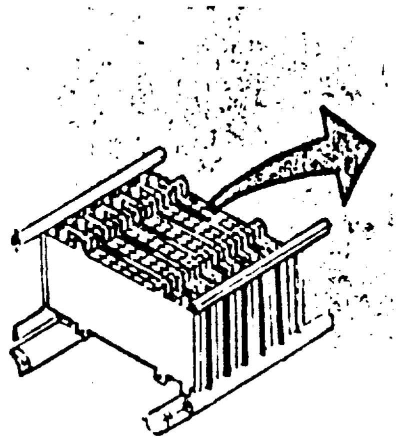
TECHNOLOGY CHALLENGES



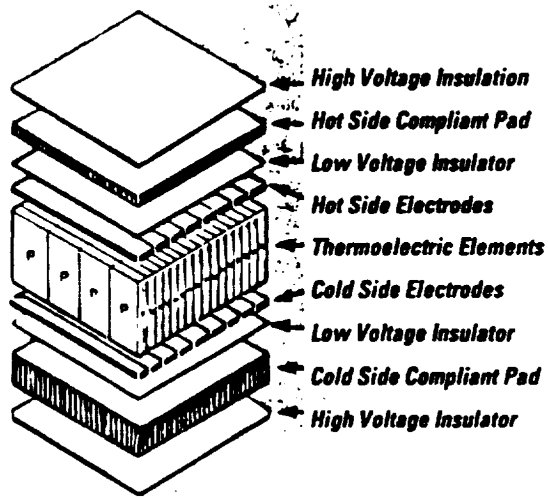
CE 3
2/15/91

Power Converter Cell Configuration

Power Converter Assembly



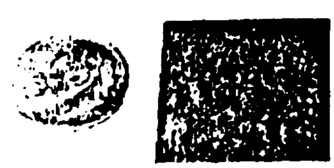
Cell Assembly



SPAC 02590-520-03

High Voltage Insulator

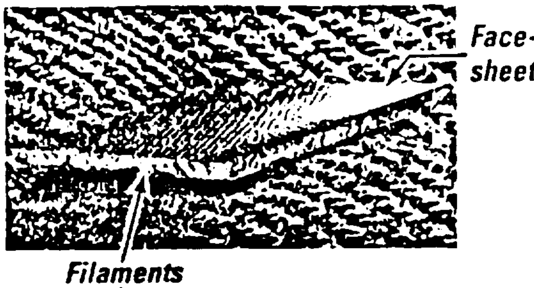
- *Accelerated Life Tests Have Demonstrated Substantial Performance and Life Margins*
  - *High Temperatures (Up to 1670 °K)*
  - *High Voltage Gradient (4 kV/cm)*
  - *Long Times (Up to One Year)*
- *Compatibility With Li Cooled Systems Proven by Analysis and Test*
- *Mechanistic Degradation Models Developed and Validated*

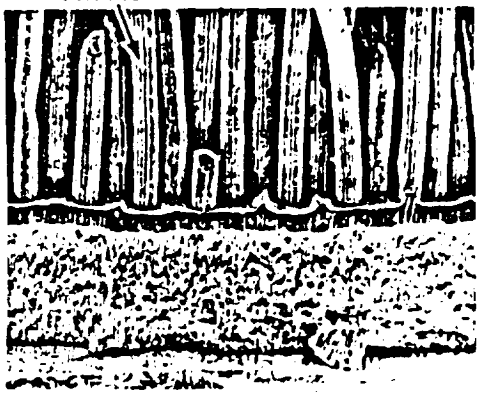


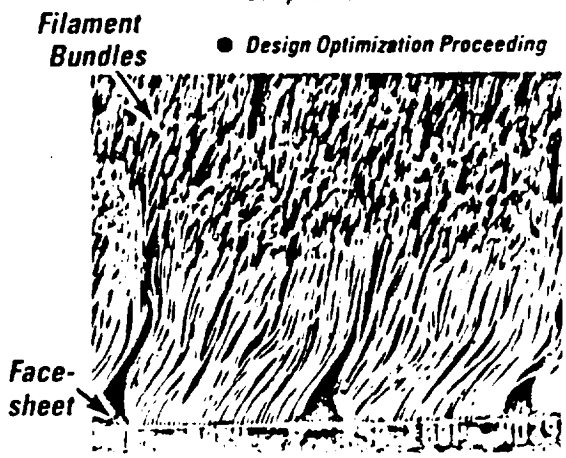
Essential Technology Demonstrated

SPAC 032 90-520-10

Compliant Pad







- Fabricability Demonstrated
  - Facesheet Materials/Thickness
  - Filament Diameters/Density
  - Pad Thickness
- Bond Strength Demonstrated
- Compliance Demonstrated
- Design Optimization Proceeding

SPAC 02 · 90 5.12 05

Space Subsystems

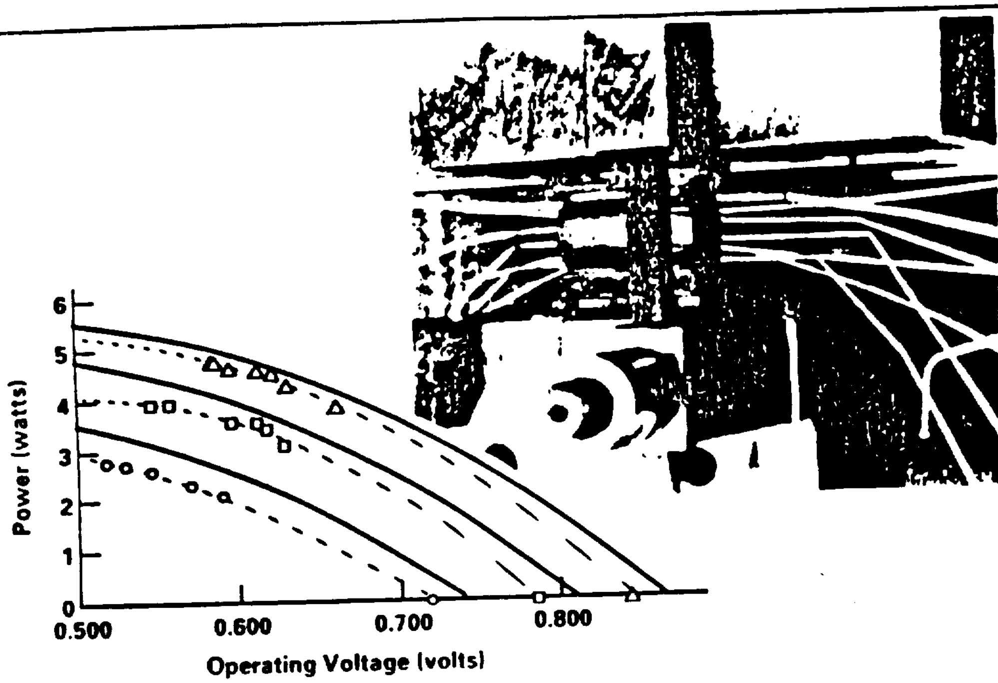
Cell Assembly

Cell Development Road Map

PD-1 ASSEMBLY VERIFICATION → PD-1 PERFORMANCE VERIFICATION → PD-2 → TA → DEV → TCA

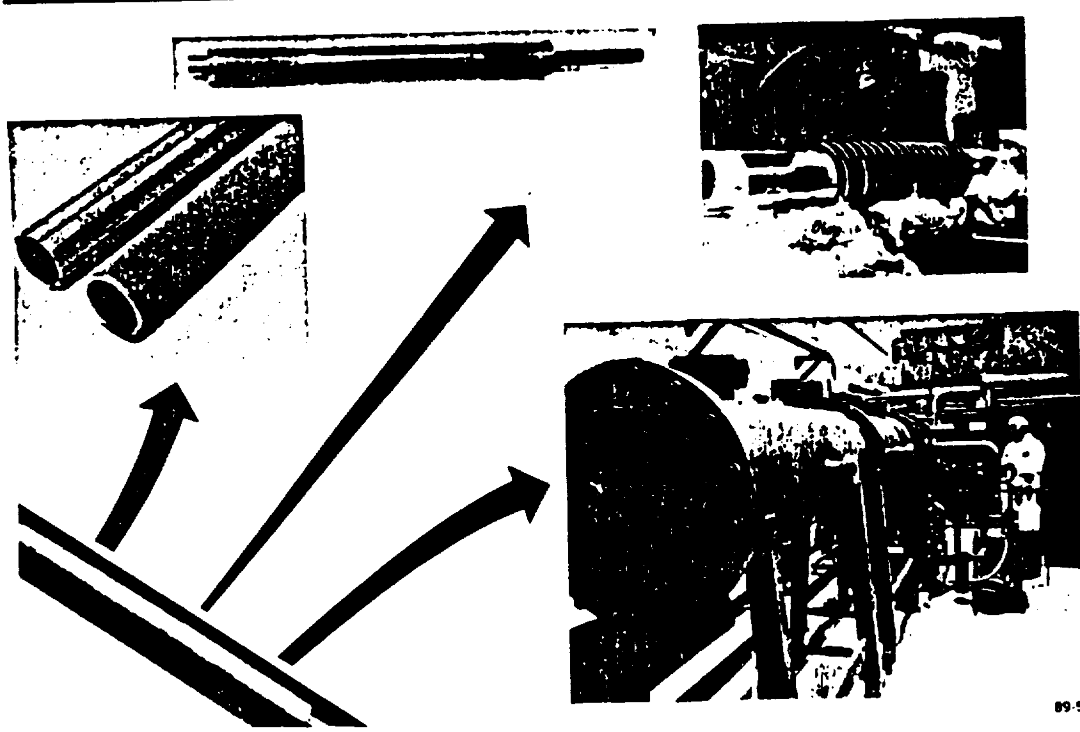
March 1989	September 1989	March 1991	October 1992		
Verified Fabrication and Assembly Processes	Verified Predictability of Performance	Test at Full Prototypic Hot Side Temperature	Prototypic Configuration	Prototypic Configuration	Prototypic Configuration and Operating Conditions
Demonstrated Structural Integrity	Demonstrated Structural Integrity	Closer to Prototypic Design Features	Verify Performance	First Array Tests	'onverter/Pump 'est
Show and Tell	Lessons Learned for PD-2	Verify Performance	Demonstration of Technology Features of GFS Design	Cell Life Tests	Array Life Tests
	Hot Side Temperature Limited by Braze				

First Generation Cell In-Gradient Test



SPAC 029 90 520 06

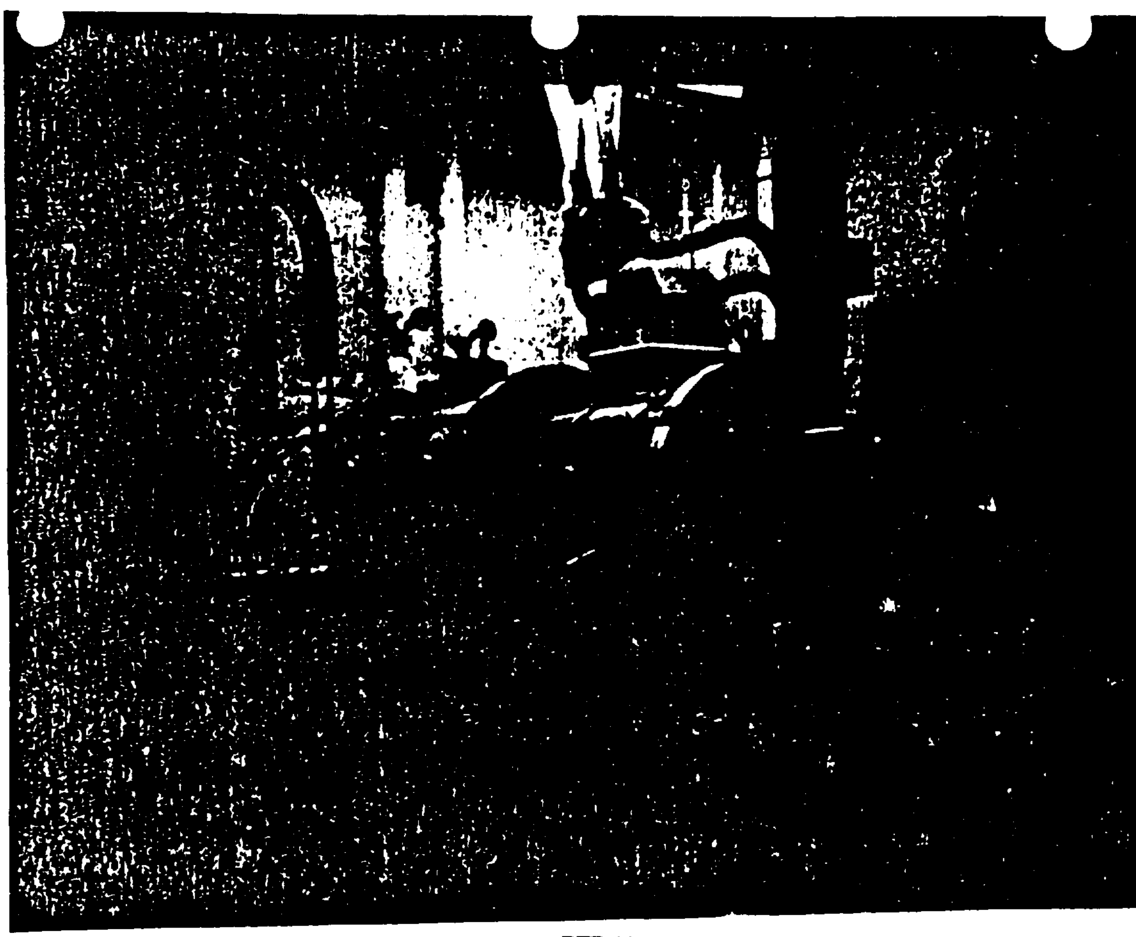
Potassium Heat Pipe Development



89-586-43

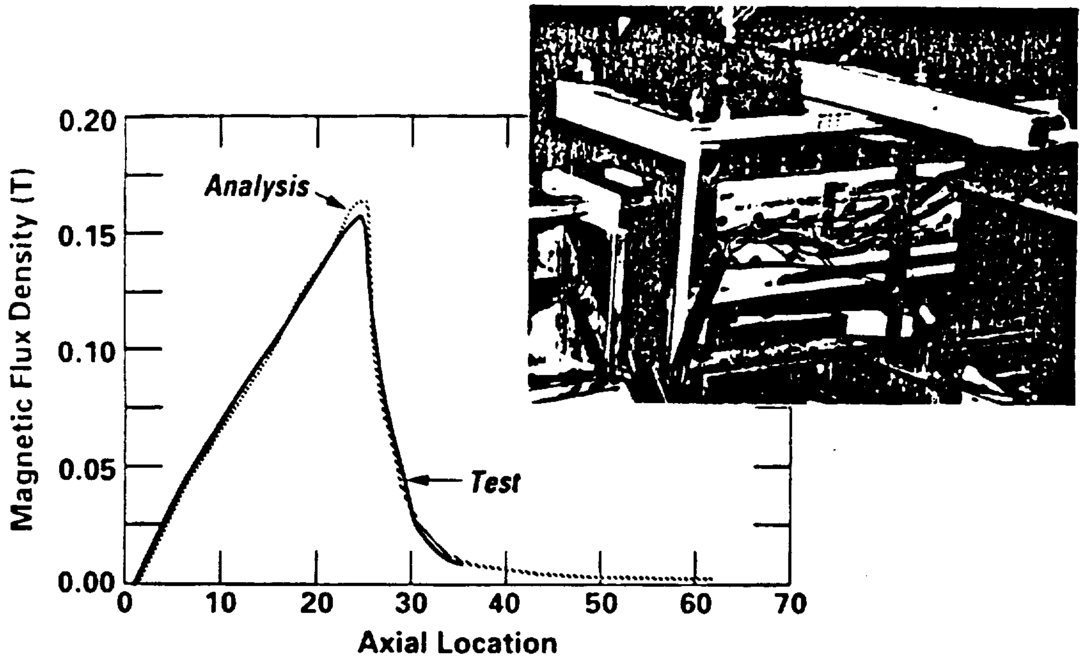
O POTASSIUM HEAT PIPE ACCOMPLISHMENTS

- DEVELOPMENT OF ETCHED TITANIUM FOIL WICKS (PREFERRED TECHNOLOGY)
- DEVELOPMENT OF SINTERED TITANIUM WICKS
- DEMONSTRATED PERFORMANCE OF NB1Zr HEAT PIPES WITH FOIL WICKS
- PRELIMINARY DEMONSTRATION OF RADIATOR THAW CONCEPT, DUCT WITH BLEED HOLES



EG19 7976 C

TEM Pump Magnetic Bench Test



NSS 090 90-520-20

EXPLORATION TECHNOL[illegible]Y

SPACE NUCLEAR POWER - SP-100
SUMMARY

- **IMPACT:**
  - PROVIDES ENABLING TECHNOLOGY FOR LUNAR/MARS BASES
  - POWER SOURCE FOR 1 - 100 kWe NEP FOR EARLY 21st CENTURY SCIENCE MISSIONS NOW BEING CONSIDERED
  - REACTOR TECHNOLOGY FOR MMWe NEP SYSTEMS FOR MARS CARGO AND PILOTED SPACE EXPLORATION MISSIONS
- **USER COORDINATION:**
  - SEI TECHNOLOGY REQUIREMENTS ARE BEING DEVELOPED COOPERATIVELY WITH CODE RZ (NUCLEAR POWER IDENTIFIED AS A HIGH PRIORITY AND ENABLING BY CODE RZ)
  - PLANETARY SCIENCE REQUIREMENTS ARE BEING DEVELOPED COOPERATIVELY WITH OSSA AND WITH JPL (NUCLEAR POWER RATED AS A HIGH PRIORITY BY OSSA IS ENABLING FOR MANY MISSIONS)
- **MAJOR TECHNICAL PROGRAMMATIC ISSUES:**
  - GENERIC TECHNOLOGY DEVELOPMENT - MEETS ALL POTENTIAL USER NEEDS
  - ABSENCE OF SPECIFIC APPROVED PROGRAM USING NUCLEAR POWER CONFUSES FIRM TECHNOLOGY READINESS REQUIREMENT DATE

ITP.RJS91-002.11

CONCLUDING REMARKS

- SP-100 IS THE NATIONAL NUCLEAR SPACE POWER PROGRAM
  - NATIONAL LEVERAGE
- PROVIDES A WIDE RANGE OF OPTIONS
  - FEW kWe's —— MMWe
- MAJOR IMPACT ON EXPLORATION MISSION
- EXCELLENT TECHNICAL PROGRESS
  - FUNDING DIFFICULTIES
- FULL-UP PROGRAM
  - DEMONSTRATES USER SUPPORT/LEVERAGE
  - TECHNICAL SUCCESS

ITP.RJS91-002.10

INTEGRATED TECHNOLOGY PLAN
FOR THE CIVIL SPACE PROGRAM

HIGH CAPACITY POWER

BY

R. J. SOVIE

Deputy Chief, Power Technology Division
NASA Lewis Research Center

ITP EXTERNAL REVIEW

JUNE 27, 1991

ITP91-002.1

NASA

HIGH CAPACITY POWER

WHAT WE WILL DISCUSS

- OBJECTIVES/BENEFITS
- MAJOR MILESTONES/SCHEDULE/BUDGET
  - BASELINE
- TECHNICAL PROGRESS
- FULL-UP PROGRAM
- Δ WITH AUGMENTED PROGRAM
- ISSUES/CONCERNS
- CONCLUDING REMARKS

ITP RJS91-001 2

CSTI HIGH CAPACITY POWER

- PROVIDE FOR INCREASED POWER, RELIABILITY AND LIFETIME FOR NUCLEAR SPACE POWER SYSTEMS USING THE SP-100 REACTOR, THROUGH ADVANCED TECHNOLOGY DEVELOPMENT IN STATIC AND DYNAMIC ENERGY CONVERSION SYSTEMS, THERMAL AND POWER MANAGEMENT SYSTEMS AND MATERIALS

ITP RJS91-001 3

SURFACE SYSTEMS/OPERATIONS

HIGH CAPACITY POWER *

OBJECTIVES

- Programmatic

  Develop and Demonstrate Low Mass, Reliable Long-Lived Power Conversion Technology for Space Nuclear Reactor Power Systems

- Technical

  Temperature - 1050K Stirling
  - 1300K Stirling and Thermoelectric

  Power - Stirling at 25 kWe/Cyl - 50 kWe Modules

  Lifetime - > 7 years

SCHEDULE

- 1992 - EOIM-3, STS-46 Flight Experiment
- 1993 - Thermoelectric Multicouple, Z = .85
- 1993 - Stirling, 1050K, 25 kWe/Cylinder, 25% eff.
- 1993 - H_2O Heat Pipe/Radiator Module Demo
- 1994 - 600K Radiator Segment Demo
- 1995 - Mfg. Specs. for Z = 1.0 Thermoelectric
- 1996 - Stirling, 1050K, 25 kWe/Cylinder, 30% eff.
- 1997 - Endurance Test, 1050K Stirling
- 1999 - Stirling, 1300K, 25 kWe/Cylinder, [illegible]% eff.

RESOURCES ($M)	CURRENT	STRATEGIC	CoF
• 1991	10.4	10.4	0
• 1992	10.6	10.6	0
• 1993	4.5	11.1	0
• 1994	4.6	16.8	0
• 1995	4.8	23.0	6.0
• 1996	5.0	30.5	5.0
• 1997	5.2	23.0	0
• 1998	-	-	5.0
• 1999	-	-	10.0

PARTICIPANTS

- Lewis Research Center

  Responsibility for Project Lead

- Jet Propulsion Laboratory

  Responsiblity for Thermoelectrics

* Note This Element is Integrated With Development of the SP-100 Space Nuclear Reactor Program

ITP91-002.2

NASA
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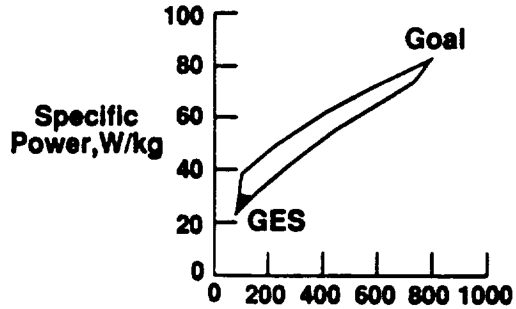
POWER TECHNOLOGY DIVISION

SPACE NUCLEAR POWER

High Capacity Power



- **Free piston Stirling converters**
- **Advanced thermal management**
- **Power management & distribution**
- **Environmental interactions**
- **Thermoelectrics**
- **Materials development**

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AEROSPACE TECHNOLOGY DIRECTORATE

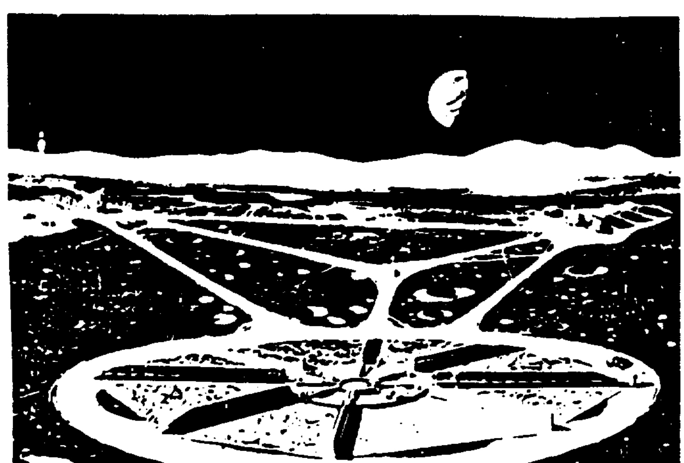
HIGH CAPACITY POWER

NASA

WHY NUCLEAR STIRLING ?

NUCLEAR-STIRLING IS AN ENABLING TECHNOLOGY PROVIDING LOW MASS, HIGH SPECIFIC POWER ELECTRICAL GENERATING SYSTEMS FOR THE MOON AND MARS

LUNAR BASE POWER SYSTEM IMLEO COMPARISON
• SAVES 1300 HLLVs vs SOA SOLAR PV
• SAVES 16 HLLVs vs ADVANCED SOLAR PV
• REQUIRES ONLY 1 LTV TO LUNAR SURFACE



550 kWe NUCLEAR-STIRLING LUNAR POWER SYSTEM

JFD91-001.4

MISSION APPLICATION

- HIGH CAPACITY POWER PROGRAM
  - SUPPORTS LUNAR/MARS BASE
  - NEP SCIENCE, CARGO
  - DYNAMIC SYSTEMS FOR SPACE PLATFORMS, DIPS
  - HEAT REJECTION FOR ALL APPLICATIONS
- **PROVIDE GROWTH AND BACK-UP FOR SP-100**
  - IMPROVED MATERIALS
  - LOWER TEMPERATURE
  - INCREASED LIFETIME

ITP RJS91-001 10

HIGH CAPACITY POWER

NASA

HIGH CAPACITY POWER BASELINE PROGRAM MAJOR MILESTONES

• FREE-PISTON STIRLING	• 1050 K, 25 kWe/CYLINDER, 30% EFF, 7 YEAR LIFE (PRESENT - 650 K, 12.5 kWe/CYLINDER, 20% EFF, 1000 HR. LIFE)
• THERMOELECTRICS	• $Z = .85 \times 10^{-3} K^{-1}$ MULTICOUPLES/CONDUCTIVELY COUPLED (PRESENT - $Z = .67 \times 10^{-3} K^{-1}$ MULTICOUPLES/RADIATIVELY COUPLED)
• THERMAL MANAGEMENT	• 500 - 550 K RADIATOR SEGMENT TEST - STIRLING COLD END (PRESENT - PAPER DESIGNS, COMPONENT PRODUCED, NO RADIATOR TESTS)
• POWER MANAGEMENT	• RAD HARD, HIGH TEMP SEMICONDUCTOR AND MAGNETICS COMPONENTS (PRESENT - RADIATION DEGRADES SEMICONDUCTORS, HIGH TEMPERATURE DEGRADES MAGNETS)
• SYSTEM DIAGNOSTICS	• FIBER OPTIC POWER SENSOR FLIGHT QUALIFIED (PRESENT - POWER SENSORS EMI SENSITIVE, FIBER OPTIC CURRENT SENSOR BREAKTHROUGH)
• ENVIRONMENTAL INTERACTIONS	• MODELS/EXPERIMENTS DEMONSTRATING LUNAR/MARTIAN/SPACE PLASMAS COMPATIBILITY OF SPACE POWER SYSTEMS (PRESENT - NO MODELS AVAILABLE - INITIAL EXPERIMENTS ON MARS ENVIRONMENT BEGINNING)

JMW91-007 4

HIGH CAPACITY POWER - BASELINE PROGRAM SCHEDULE

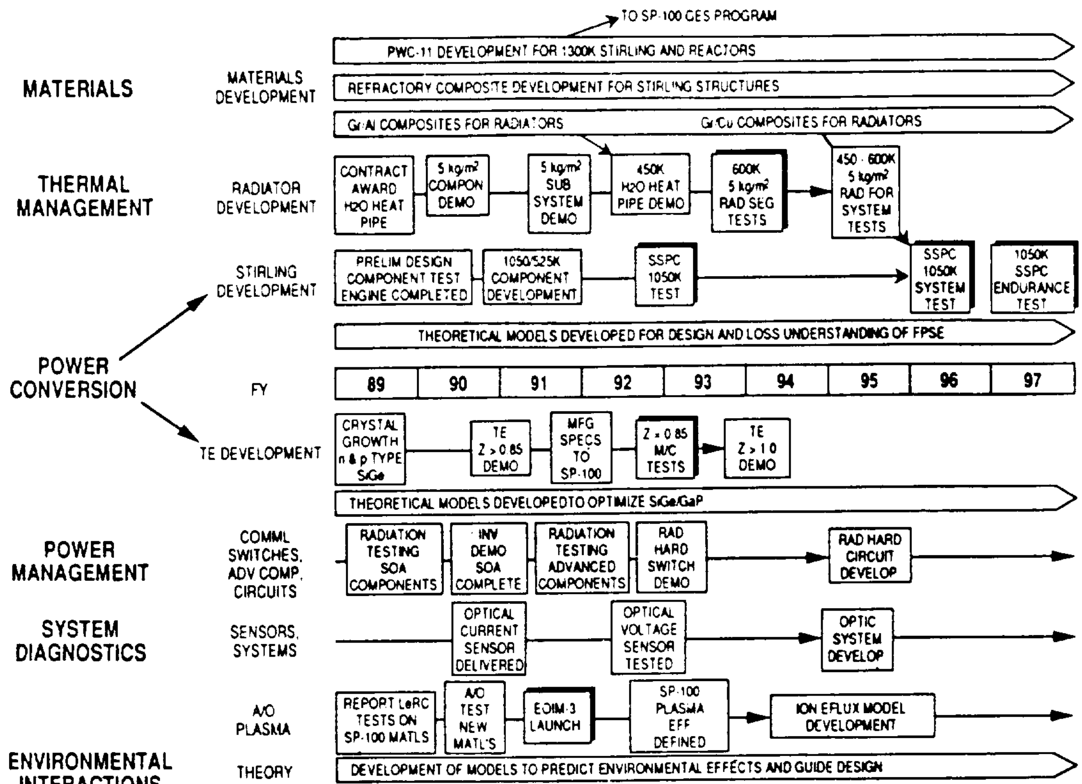
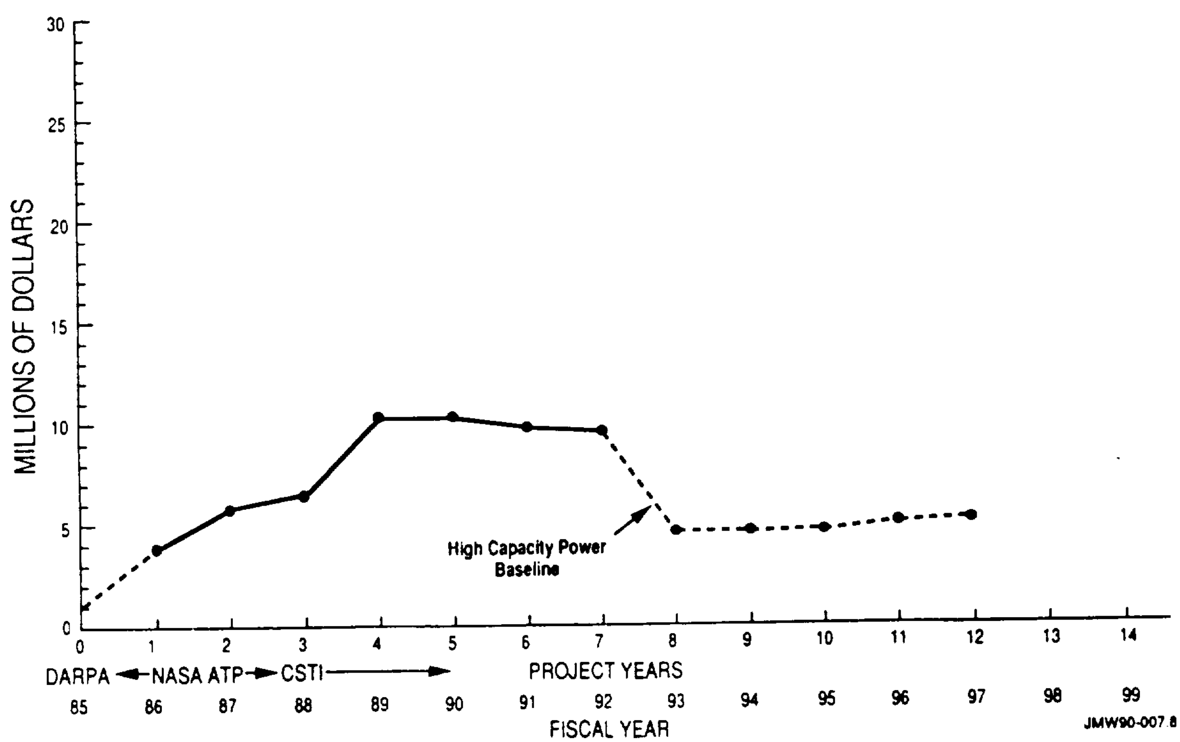


Figure 7

JMW90-004.2

HIGH CAPACITY POWER

GROSS FUNDING HISTORY/PROJECTIONS NASA SP-100 ATP - HIGH CAPACITY POWER



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ADVANCED STIRLING

MAJOR OBJECTIVE:

DEMONSTRATE THE PERFORMANCE, SPECIFIC POWER, LIFETIME, RELIABILITY, OF A 25 kWe/PISTON, 1300 K, $T_R = 2$, FPSE FOR LUNAR BASE APPLICATION

- DEMONSTRATE PERFORMANCE OF SUB-SYSTEMS
  (Heat Transport, Power Conversion, Heat Rejection, PMAD)
- INTEGRATE SUB-SYSTEMS/DEMONSTRATE SYSTEM OPERATION

ITP JMW91-001 2

SSPC SUPPORTING R&T

OBJECTIVE:

- TO ESTABLISH A STRONG FPSE TECHNOLOGY BASE

ACTIVITIES:

IN-HOUSE ENGINES
- SPRE
- RE-1000 HEAT PIPE
- RE-1000 HYDRAULIC
- SPIKE
- 1.5 kWe SOLAR DYNAMIC DESIGN

"Notice all the computations, theoretical scribblings and lab equipment, Norm. . . . Yes, curiosity killed these cats"

JED90-002.6

ANALYSIS
- CODE DEVELOPMENT
  HFAST, GLIMPS, CFD
- LOSS UNDERSTANDING
  CONTRACTS (3)
  GRANTS (8)
  ANNUAL WORKSHOP
- PARTICIPANTS
  U. OF MINNESOTA (3)
  CLEVELAND STATE (2)
  MIT
  U. OF PITTSBURGH
  CASE-WESTERN RESERVE
  SUNPOWER
  MTI
  GEDEON ASSOCIATES
  NASA-LeRC

COMPONENT TECHNOLOGY
- MAGNETICS
- LINEAR ALTERNATORS
- CONTROLS
- LOAD INTERACTION
- HEAT PIPES
- HEAT EXCHANGERS
- MATERIALS/JOINING
- MAGNETIC BEARINGS
- HIGH TEMPERATURE INSTRUMENTATION

FREE-PISTON STIRLING ENGINES

KEY PROGRAM ELEMENTS

SCALING: 12.5 → 25 kWe/P

SPECIFIC MASS: 9 kg/kWe <6 kg/kWe

EFFICIENCY: 20 → 30 (35)

LIFETIME: ≥ 7 YEARS

OPERATING TEMPERATURE: 650 K → 1050 K (1300 K)

APPROACH

COMPONENT DEV. TESTING → SUB-SYSTEMS → SYSTEM TESTS

STRONG AS SUPPORTING ANALYSIS

ITP RJS91-001 5

HIGH CAPACITY POWER

STIRLING DEVELOPMENT

BASELINE PROGRAM

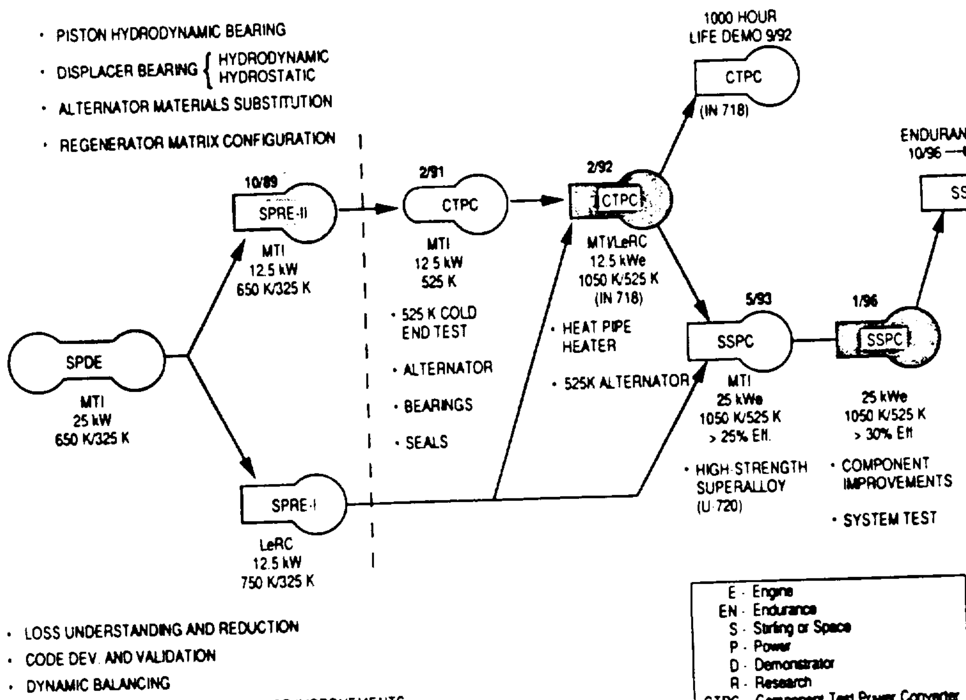
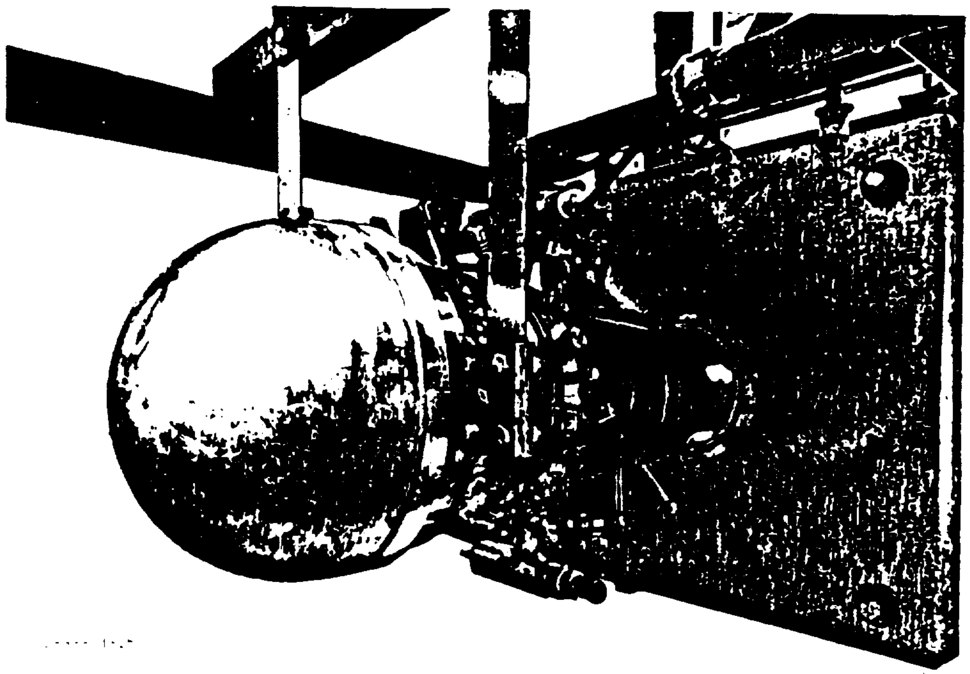


Figure 1

JMW90-005 7

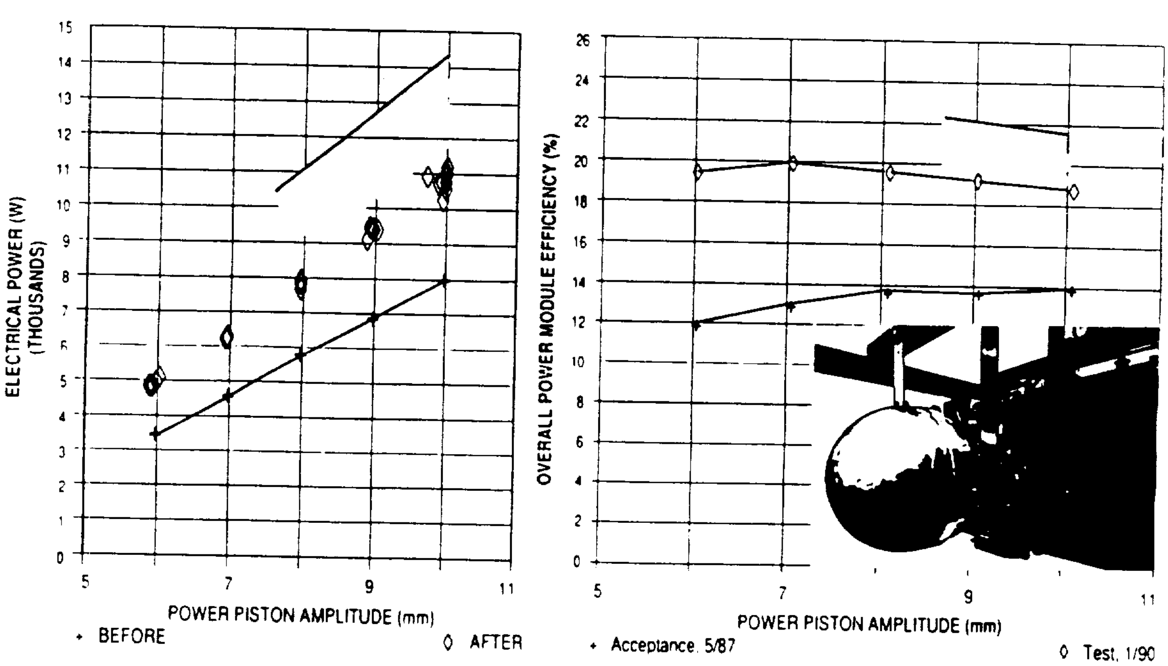
FREE-PISTON STIRLING
SPACE POWER RESEARCH ENGINE



HIGH CAPACITY POWER NASA

SPRE TEST

150 Bar, T_{HOT} = 650 K, TR = 2.0

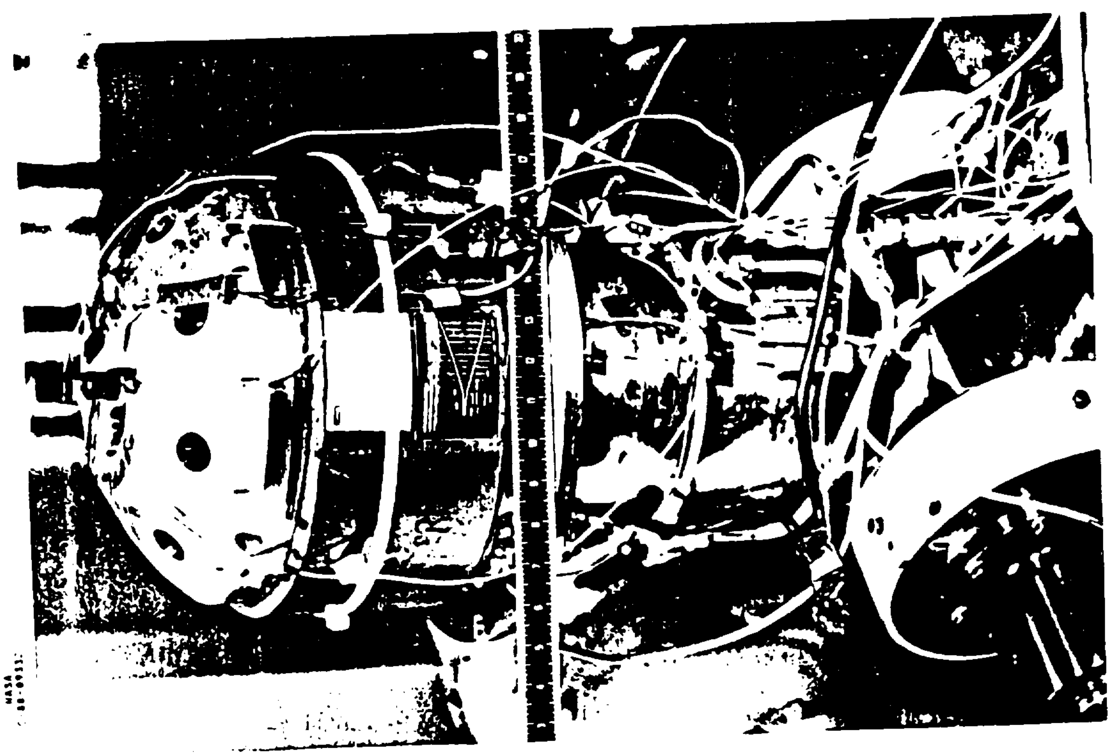


JED90 001

SPRE TECHNICAL PROGRESS

- SUCCESSFUL DEMONSTRATION OF:
  - 12.5 kWe/PISTON
  - $T_R = 2$
  - NON-CONTACTING GAS BEARINGS (HYDROSTATIC & HYDRODYNAMIC)
  - STABLE OPERATION WITH CENTERING PORTS REDUCED FROM 6 TO 2
  - RADIAL CLEARANCE INCREASED FROM 2 mils TO 5 mils
    - PREDICTED POWER LOSS
    - NO CHANGE IN EFFICIENCY
  - VALIDATED DESIGN CODES
  - DEMONSTRATED LINEAR ALTERNATOR EFFICIENCY > 90% AT 325 K

ITP JMW91-001.9



HIGH CAPACITY POWER

NASA

LINEAR ALTERNATOR TECHNICAL PROGRESS

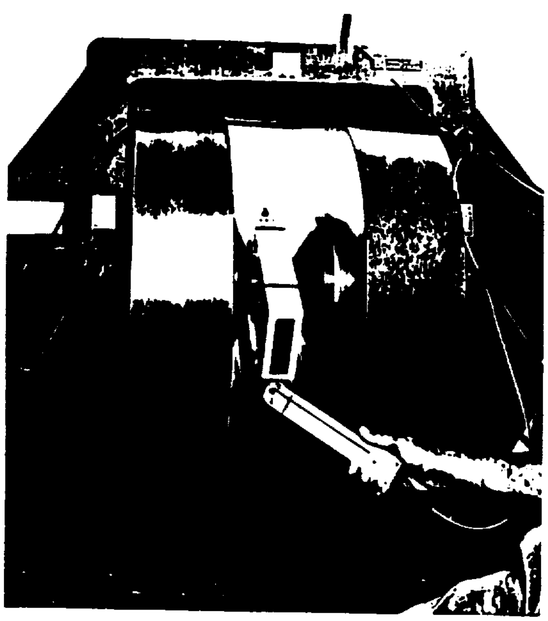
- LINEAR ALTERNATOR DYNAMOMETER QUANTIFIED EDDY CURRENT LOSSES
  - VERIFIED IMPROVED PERFORMANCE WITH NON-MAGNETIC SUPPORT STRUCTURE
- LINEAR ALTERNATOR "SHAKE AND BAKE" TEST RIG VALIDATES INSULATION AND STRUCTURAL INTEGRITY

ITP JMW91-001 10

HIGH CAPACITY POWER

NASA

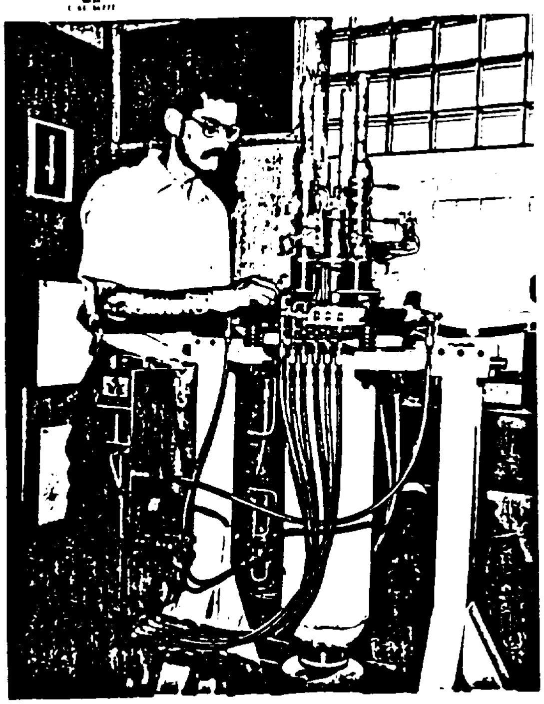
HIGH TEMPERATURE MAGNETICS TECHNICAL PROGRESS



- 5 COMMERCIAL MATERIALS EVALUATED
- SAMARIUM $_2$ COBALT $_{17}$ CHOSEN FOR 525K
- DEFINES DESIGN MARGINS ON TEMPERATURE AND CURRENT
- STABILITY - CYCLING AND LIFETIME UNDER INVESTIGATION

JED90 007 2

FREE-PISTON STIRLING ENGINE ADVANCED HEAT EXCHANGER TESTS



- MEASURED HEAT PIPE TEMPERATURE DROPS AGREE WITH THE ANALYTICAL PREDICTIONS
- OPERATED WITH HEAT PIPE TEMPERATURE AS HIGH AS 1050K
- HEATER METAL AND GAS TEMPERATURE PROFILES ARE BEING STUDIED TO BETTER UNDERSTAND HEAT FLUX DISTRIBUTION
- HEAT EXCHANGERS WILL BE CHARACTERIZED WITH HEAT PIPES OPERATING WITH GRAVITY AND AGAINST GRAVITY

HIGH CAPACITY POWER NASA

WE HAVE DEMONSTRATED

12.5 kWe/PISTON

EFFICIENCY = 20%

$T_R = 2.0$

$$\frac{T_H = 650\text{ K}}{T_C = 325\text{ K}}$$

DATA, ANALYSIS PROVIDE CONFIDENCE TO PROCEED TO THE NEXT GENERATION ENGINE

ITP JMW91-001 11

STIRLING SPACE POWER CONVERTER PROGRAM

PHASE TWO 1050K SUPERALLOY COMPONENT TEST POWER CONVERTER (CTPC)

OBJECTIVE:

TO PROVIDE A LOW-COST, LOW-RISK AND SHORT SCHEDULE APPROACH TO DEVELOP ALL COMPONENT TECHNOLOGIES FOR THE 25 kWe 1050 K SUPERALLOY STIRLING SPACE POWER CONVERTER

PROGRAM GOALS:

END OF LIFE POWER	25 kWe
EFFICIENCY	> 25% @ Tr = 2.0
LIFE (DESIGN)	60,000 HOURS
VIBRATION	< .04 mm (OPPOSED PISTON)
BEARINGS	NON CONTACTING (GAS FILM)
SPECIFIC MASS	< 6 kg/kWe
HOT END	HEAT PIPE

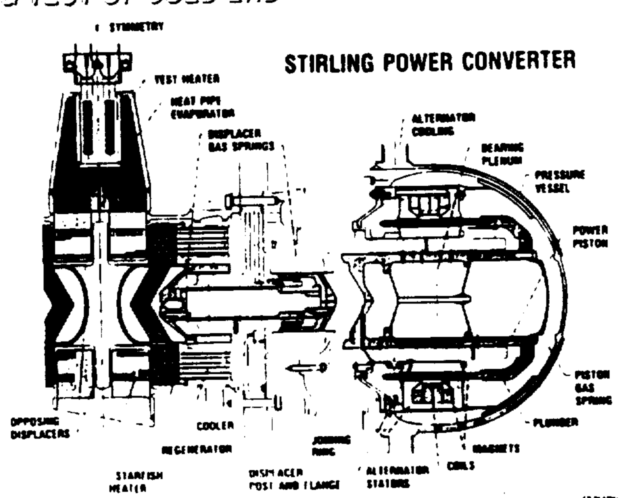
JED91-002.3

HIGH CAPACITY POWER NASA

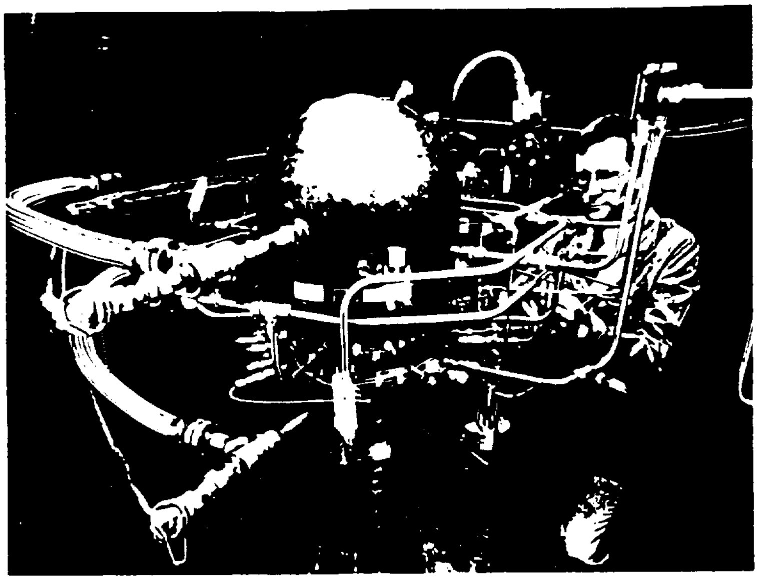
STIRLING SPACE POWER CONVERTER PROGRAM
PHASE TWO
1050 K SUPERALLOY COMPONENT TEST POWER CONVERTER (CTPC)

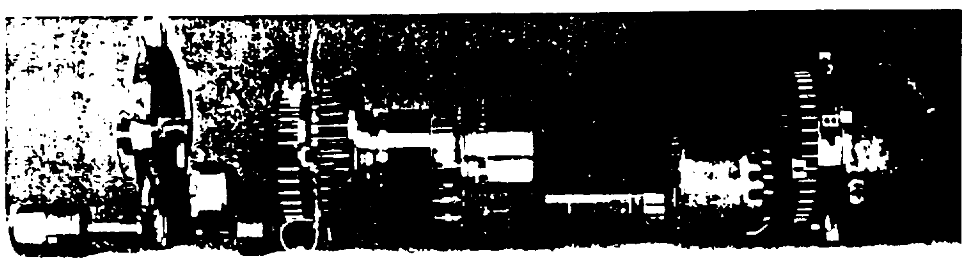
FIRST MOTORING TEST OF COLD END

- 12.5 kWe DESIGN
- MOTORED AT 70 Hz (4/15/91)
- "NEW" HYDROSTATIC BEARING SYSTEM
- NO RUBS
- START OF MTI/CTPC TEST PROGRAM



COMPONENT TEST POWER CONVERTER (CTPC)
COLD END MOTORING TEST





HIGH CAPACITY POWER

NASA

WILL IT REALLY WORK IN SPACE?

STIRLING MACHINES (CRYOCOOLERS) HAVE ALREADY FLOWN IN SPACE

- 7 FLIGHTS HAVE BEEN IDENTIFIED (6 USA/1 USSR)
- DEMONSTRATED OPERATION FROM HOURS TO 6 YEARS
- KINEMATIC STIRLING TECHNOLOGY
  - STIRLING CRYOCOOLER PROTOTYPES DESIGNED FOR TERRESTRIAL APPLICATION

PLANNED LONG-LIFE CRYOCOOLER MISSIONS - FREE-PISTON STIRLING TECHNOLOGY

- **7 FLIGHTS PLANNED WITH FLEXURE BEARING SYSTEM**

- ALONG TRACK SCANNING RADIOMETER -	1991
- IMPROVED STRATOSPHERIC AND MESOSPHERIC SOUNDER -	1991
- HIGH TEMPERATURE SUPERCONDUCTIVITY EXPERIMENT -	1992
- X-RAY SPECTROMETER -	1996
- EARTH OBSERVING SYSTEM INSTRUMENTS -	'96, '97, '98

- **1 FLIGHT PLANNED WITH GAS BEARING SYSTEM**

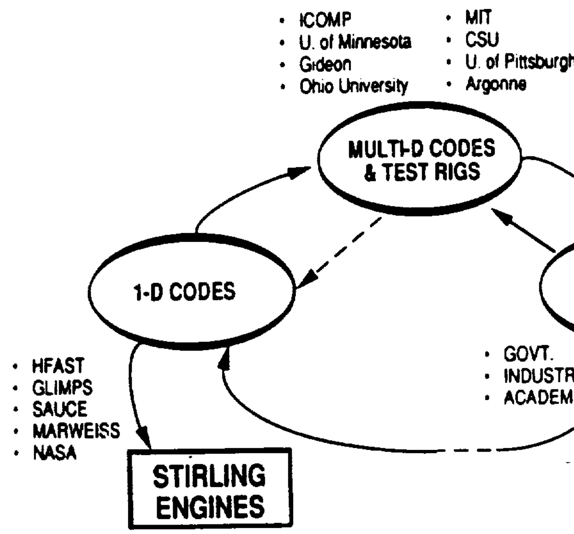
- SDI/SPAS EXPERIMENT	1994

- TO DEMONSTRATE THAT FREE-PISTON STIRLING CRYOCOOLERS WITH GAS BEARINGS CAN SURVIVE LAUNCH ENVIRONMENTS

IED01.002.5

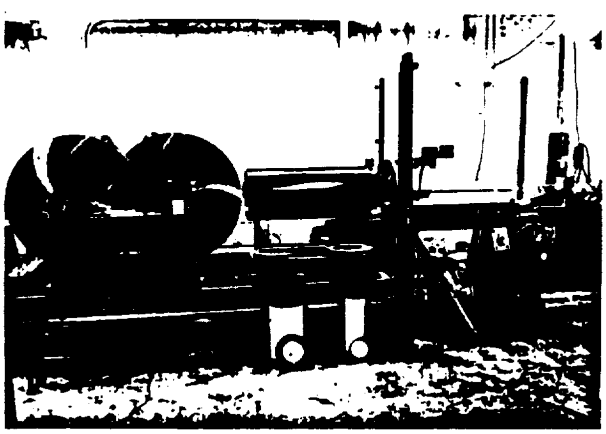
CODE DEVELOPMENT PROGRESS

- IMPROVED UNDERSTANDING OF FLUID FLOW AND HEAT TRANSFER IN HEATERS, COOLERS, AND GAS SPRINGS WITH OSCILLATING FLOW
- MULTI-DIMENSIONAL CODES ⟶ INSTANTANEOUS HEAT TRANSFER AND FLUID FRICTION COEFFICIENTS FOR 1-D DESIGN CODES



ITP.JMW91-001.12

OSCILLATING-FLOW RIGS



MINNESOTA

MIT

OHIO U.

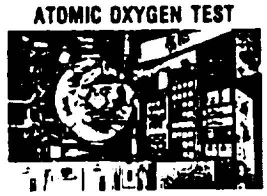
GOVERNMENT IN-HOUSE TEST FACILITIES

SPACE POWER RESEARCH ENGINE

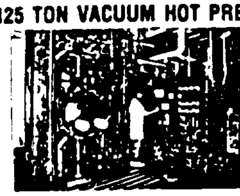
STIRLING RE 1000 HEAT PIPE TEST

LINEAR ALTERNATOR RESEARCH

ATOMIC OXYGEN TEST

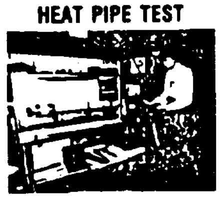


125 TON VACUUM HOT PRESS



HIGH TEMPERATURE VACUUM CREEP TEST

HEAT PIPE TEST



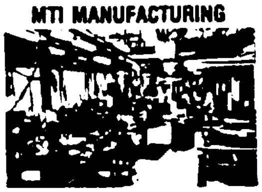
HI-TEMP CALORIMETRIC VACUUM EMISSOMETER

CD-89-41441

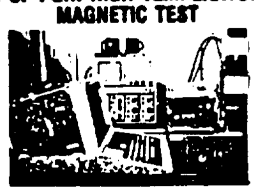
CSTI HIGH CAPACITY POWER
NASA Lewis Research Center

INDUSTRY/UNIVERSITY TEST FACILITIES

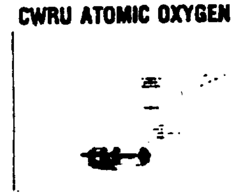
MTI MANUFACTURING



U. OF PGH. HIGH TEMPERATURE MAGNETIC TEST

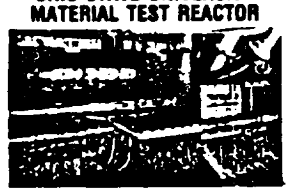


CWRU ATOMIC OXYGEN TEST



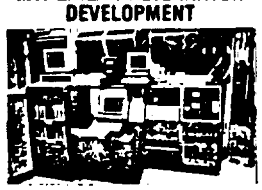
MTI FREE-PISTON STIRLING

OHIO STATE UNIVERSITY MATERIAL TEST REACTOR



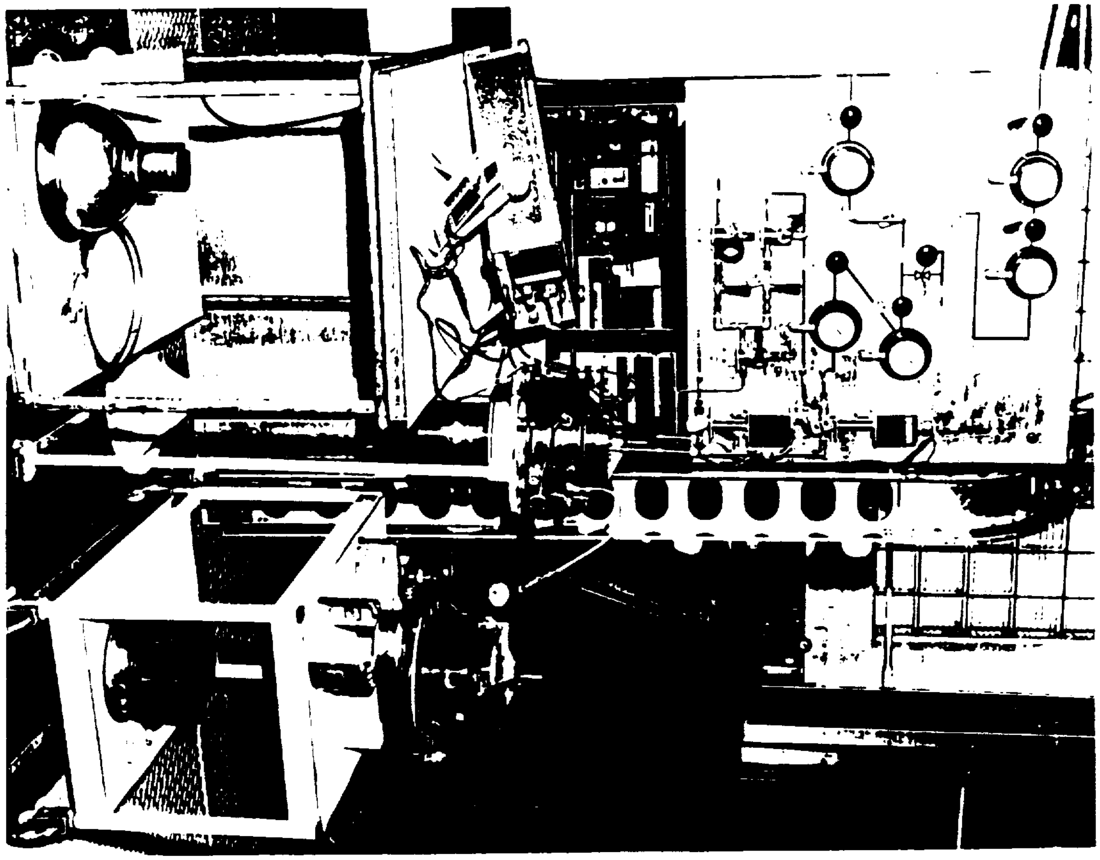
SUNPOWER OSCILLATING/STEADY-STATE FLOW TEST

MTI LINEAR ALTERNATOR DEVELOPMENT



UNIVERSITY OF CINCINNATI GAMMA TEST

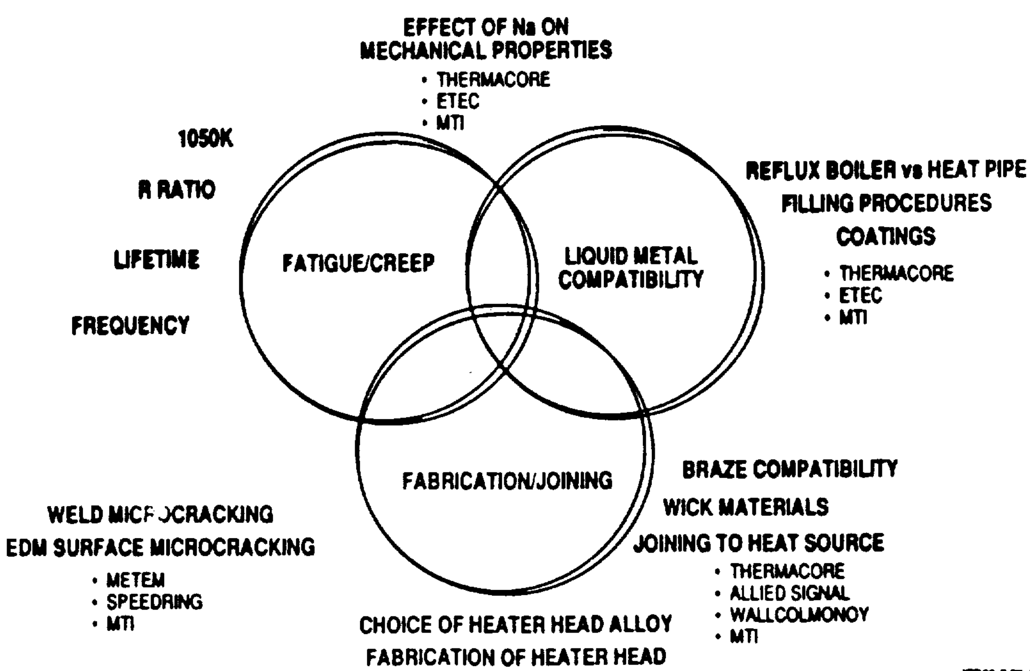
CD-89-41442



CSTI HIGH CAPACITY POWER

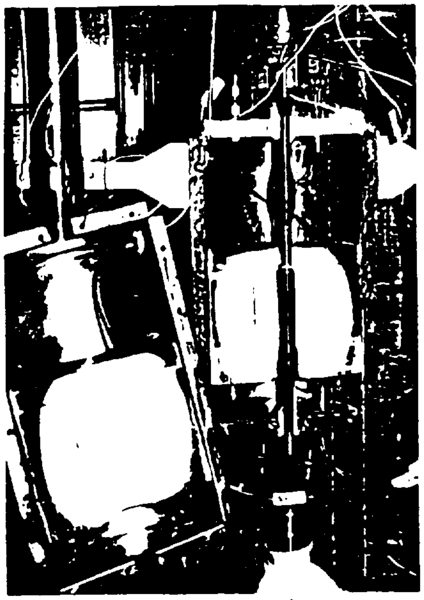
NASA

MATERIALS STUDIES FOR THE STIRLING SPACE POWER CONVERTER



JED89-8.02 41

SODIUM HEAT PIPE FATIGUE TESTS
THERMACORE/MTI



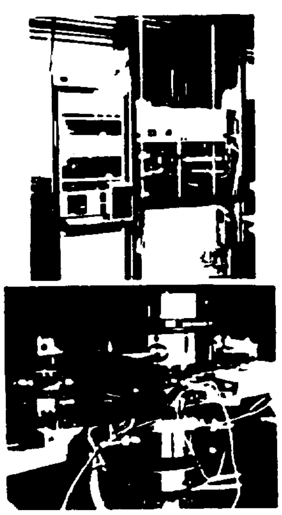
NASA
C-90-09868

- SIMULATES STARFISH HEATER LOADINGS AND ENVIRONMENT
  - SODIUM HEAT PIPE
  - INCONEL 718 (CTPC MATERIAL)
  - EVALUATES CORROSION EFFECTS
  - EVALUATES CREEP AND HIGH CYCLE FATIGUE
- 4 HEAT PIPES FABRICATED
  - 1 CUT APART FOR O_2 TEST
    - [illegible] PPM
    - [illegible] 2400 PPM
  - 3 INSTALLED IN FATIGUE TEST RIG
- ETEC PUMPED LOOP IDENTIFIED AS SUITABLE FILL TECHNIQUE

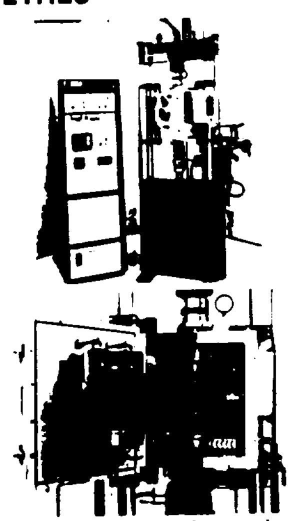
National Aeronautics and Space Administration
Lewis Research Center

AEROSPACE TECHNOLOGY DIRECTORATE NASA

BASE TEST SYSTEMS CAN BE EASILY UPGRADED TO TEST REFRACTORY METALS



From superalloys base test system



To refractory metal upgrade of base test system

CD-90-48247

STIRLING MATERIALS PROGRESS

- CERAMIC COATINGS - MAGNET INSULATORS
- NON-MAGNETIC ALTERNATOR SUPPORT STRUCTURES
- REFRACTORY MATERIALS - 1300 K CONVERTER
- STEM AND EDM TECHNIQUES - HOT END MATERIALS
- TRANSIENT LIQUID PHASE DIFFUSION BONDING } UDIMET 720
  EB WELDING
- LOW OXYGEN FILL TECHNIQUES - Na HEAT PIPES
- VISCOPLASTIC/INELASTIC ANALYSIS & TESTING - LONG LIFE DESIGN

ITP.JMW91-001.14

HIGH CAPACITY POWER

NASA

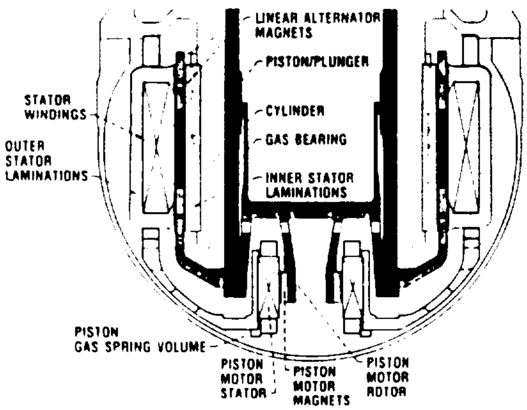
STIRLING SYSTEMS PROGRESS

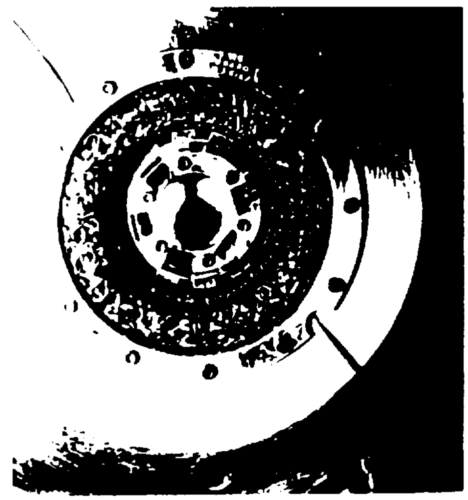
- LUNAR BASE REFRACTORY STIRLING-NUCLEAR INTERFACE CONCEPTS
- SYSTEM RESPONSE TRANSIENTS
- MULTIPLE CONVERTER INTEGRATION & INTERACTION

ITP.JMW91-001.13

SPIN-MOTOR FOR PISTON-CYLINDER HYDRODYNAMIC GAS BEARING (DEMONSTRATED ON SPRE)

SCHEMATIC SHOWING PISTON SPIN-MOTOR FOR PISTON-CYLINDER HYDRODYNAMIC GAS BEARING CONCEPT FOR A FREE-PISTON STIRLING ENGINE





NON-CONTACTING BEARINGS TECHNOLOGY PROGRESS

- HYDROSTATIC BEARING LOSSES REDUCED 50%
- HYDRODYNAMIC BEARING DEMONSTRATED
- "NEW" HIGH STIFFNESS, ULTRA STABLE HYDRODYNAMIC BEARING IDENTIFIED
- MAGNETIC BEARINGS VIABLE FOR HIGH POWER CONVERTERS
- OTHER NON-CONTACTING BEARINGS UNDER INVESTIGATION

ITP JMW91-001 15

NASA

REFERENCE ENGINE DESIGN GUIDING EFFORT

- NEW "RELATIVE DISPLACER" DESIGN REDUCES COMPLEXITY, IMPROVES MANUFACTURABILITY AND RELIABILITY, IMPROVES POWER AND EFFICIENCY (+2% POINTS)

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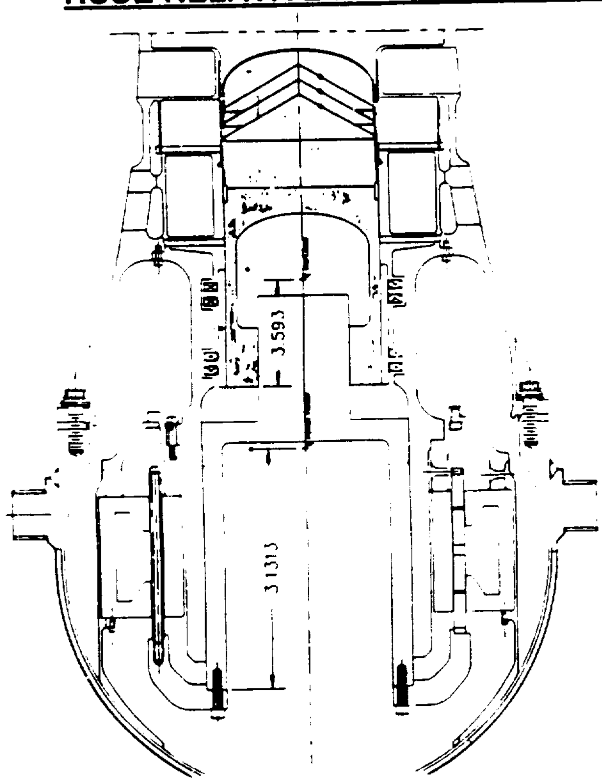
HIGH CAPACITY POWER

NASA

RSSE RELATIVE DISPLACER GAS SPRING CONFIGURATION



- REDUCED COMPLEXITY OF DISPLACER DRIVE
- IMPROVED MANUFACTURABILITY
- IMPROVED RELIABILITY
- ACCEPTS MAGNETIC BEARINGS
- INCREASED POWER DENSITY
- APPROACHES 30% EFFICIENCY

JED-90Q 03 3

ADVANCED THERMOELECTRICS

MAJOR OBJECTIVES:

DEVELOP SiGe/GaP n-LEG AND p-LEG TO PRODUCE THE $Z = .85 \times 10^{-3}\ K^{-1}$ SPECIFIED FOR THE SP-100 REACTOR SYSTEM

- OPTIMIZE DOPANTS. ADD SCATTERING CENTERS
- DETERMINE MANUFACTURING SPECIFICATIONS
- PROCURE AND TEST MODULES/MULTICOUPLES FOR ACCELERATED LIFETIME MEASUREMENTS

ITP JMW91-001 3

THERMOELECTRIC DEVELOPMENT

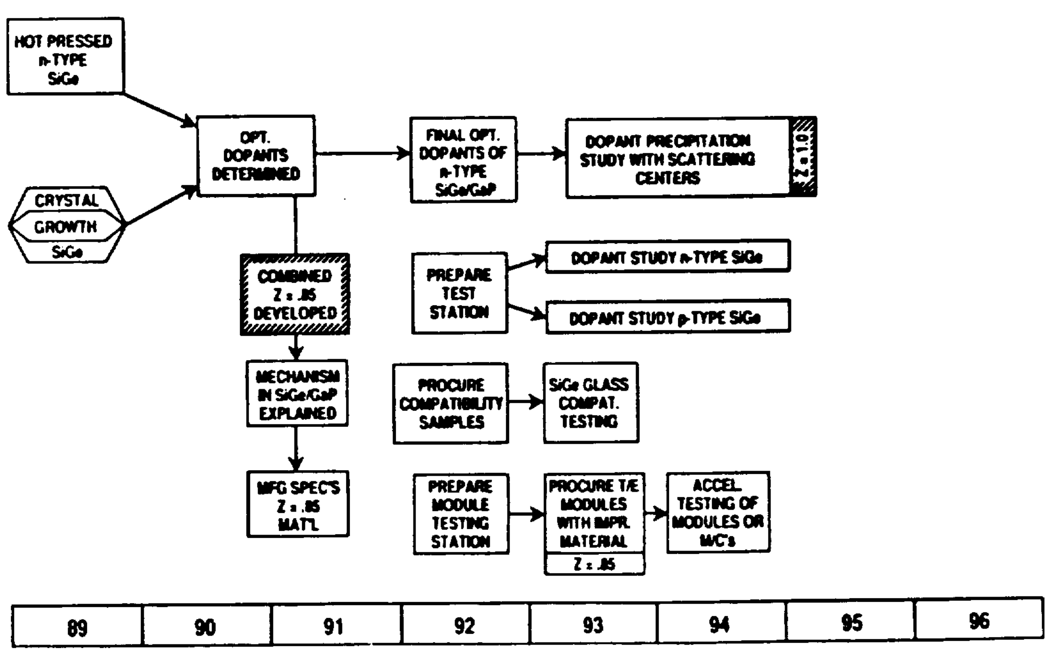
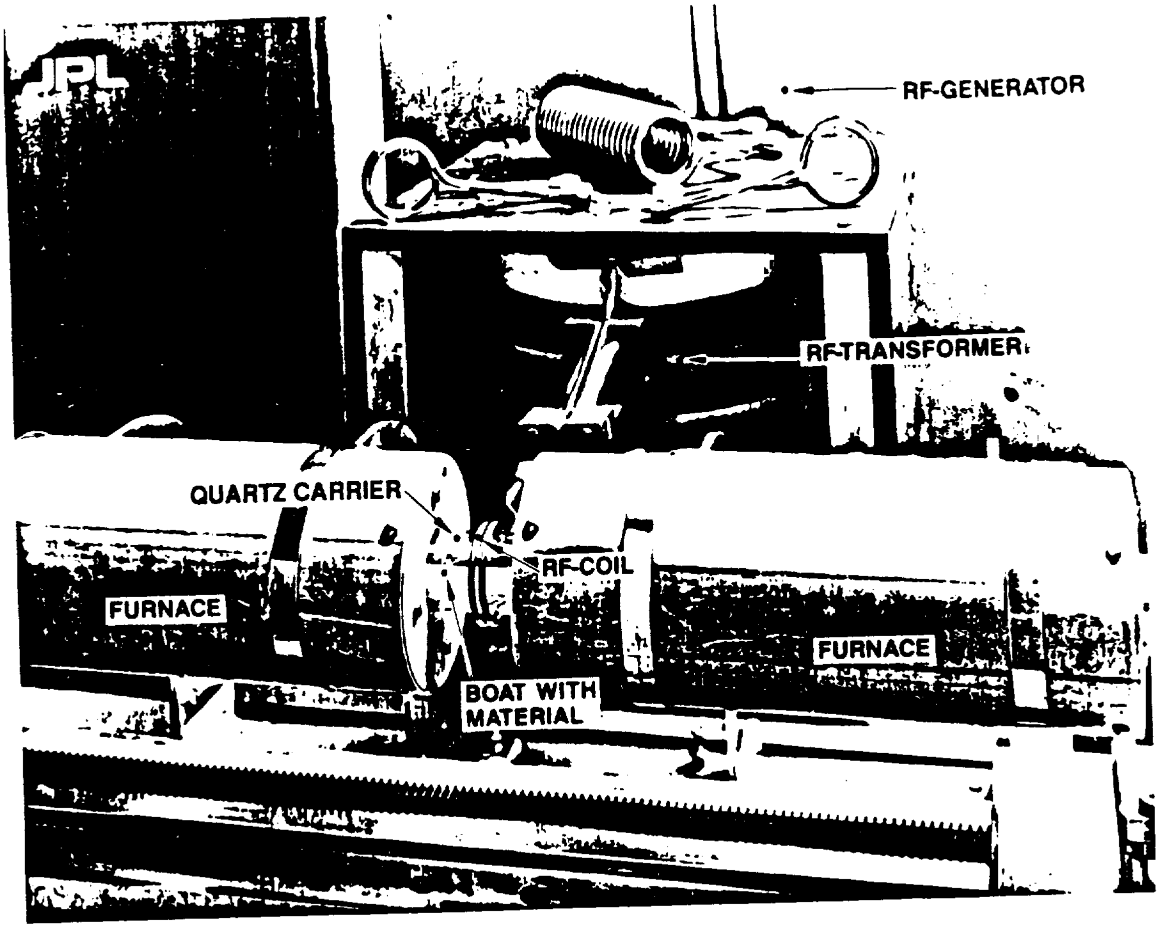
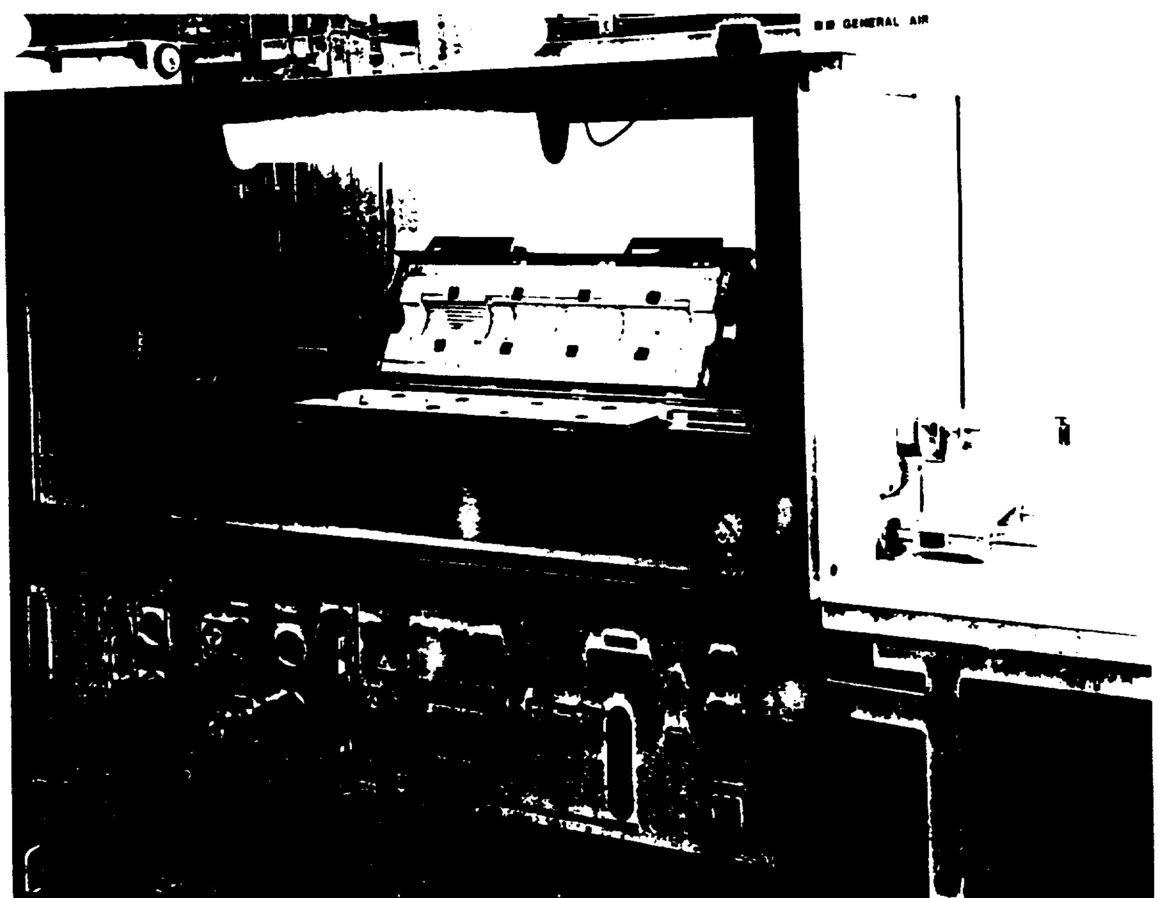


Figure 6

JMW90-004 3


JPL
RF-GENERATOR
RF-TRANSFORMER
QUARTZ CARRIER
RF-COIL
FURNACE
FURNACE
BOAT WITH
MATERIAL



ADVANCED THERMOELECTRICS - BASELINE PROGRAM

THERMOELECTRICS GOALS:

- REPRODUCIBLY OBTAIN n-TYPE SiGe/GaP with Z = .9 - 1.0 x 10^{-3} K^{-1}
  - ADD INERT SCATTERING CENTERS TO INCREASE Z TO 1.1 - 1.2 x $10^{-3}K^{-1}$
- INCREASE Z OF p-LEG TO = .70 - .75 x 10^{-3} K^{-1} WITH SCATTERING CENTERS
  - RESULTS IN COMBINED Z TO .85 - .90 x $10^{-3}K^{-1}$ BETWEEN 600 - 1000 °C

PRESENT STATUS

N-LEG: 9 SAMPLES Z BETWEEN 0.85 AND 1.0 x 10^{-3} K^{-1}

CANNOT FABRICATE HIGHEST Z SAMPLES AT WILL

CAN FABRICATE HEAVILY OVERDOPED SAMPLES, MUST REDUCE CARRIER CONCENTRATION

P-LEG: INCREASED Z 10 - 15% (.6 x 10^{-3} K^{-1}) BY OPTIMIZING BORON CONTENT

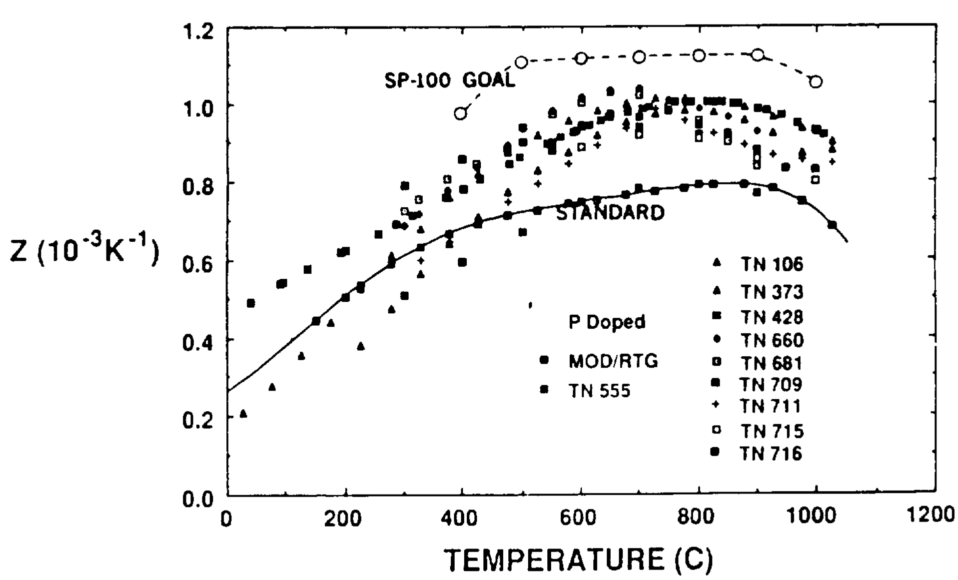
SMALL INERT PARTICLES BEING ADDED TO REDUCE THERMAL CONDUCTIVITY

MODEL PREDICTS Z INCREASE OF 40% POSSIBLE WITH PARTICULATE SCATTERING

JMW91-007 5

JPL

IMPROVED n-TYPE SiGe/GaP



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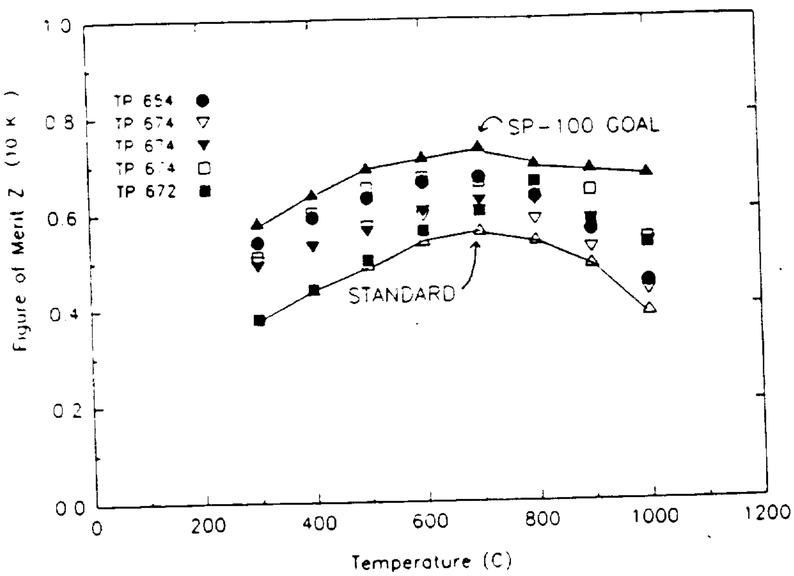
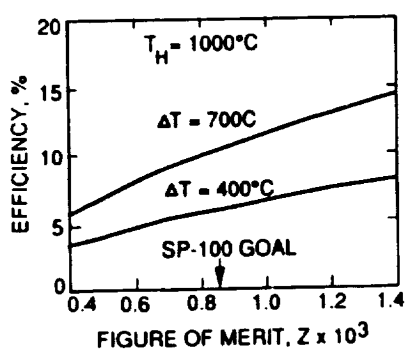
Z FOR p-TYPE SiGe

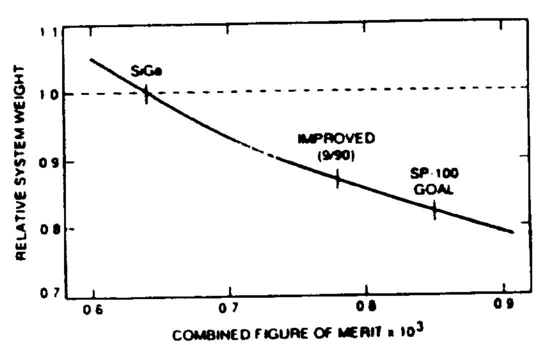


JPL

Los Alamos

OVERALL T/E IMPROVEMENT





• SP-100 GOAL OF Z_{np} = 0.85 (B.O.L.) IN SIGHT

CE-4
2/15/91

HIGH CAPACITY POWER

NASA

THERMAL MANAGEMENT

MAJOR OBJECTIVES:

DEVELOP AND DEMONSTRATE ADVANCED THERMAL MANAGEMENT CONCEPTS FOR BOTH THERMOELECTRIC AND STIRLING CONVERSION SYSTEMS

STIRLING - RADIATOR AT 475 - 600 K, 5 kg/m2 , 10 YEAR LIFETIME, .99 RELIABILITY

- HOT SIDE HEAT EXCHANGERS AND PUMPS
  - Low Mass, High Performance, Superalloy and Refractory
- COLD SIDE HEAT EXCHANGERS AND PUMPS
  - Low Mass, High Performance

THERMOELECTRIC - RADIATOR AT 800 - 900 K, 5 kg/m2 , 10 YEAR LIFETIME, .99 RELIABILITY

DEMONSTRATE PERFORMANCE OF SUB-SYSTEMS (Heat Pipes, Pumps, Heat Exchangers)

INTEGRATE RADIATOR SEGMENTS AND OTHER SUB-SYSTEMS INTO STIRLING SYSTEM TEST AT 1050K (1997) AND 1300K (1999)

ITP JMW91-001 4

EXPLORATION TECHNOLOGY

THERMAL MANAGEMENT

PROJECT
KEY ELEMENTS

ADVANCED RADIATOR SEGMENT DEVELOPMENT

- **TECHNOLOGY ⟶ COMPONENT ⟶ SUBSYSTEM ⟶ RADIATOR SEGMENT**
  - 875 K HEAT PIPE WITH FINS FOR THERMOELECTRIC
  - 600 K LiNaK PUMPED LOOP FOR STIRLING
- **SURFACE MORPHOLOGY**
  - EMISSIVITY >.85 WITH SURFACE TREATMENT, NO COATINGS
- **MATERIALS DEVELOPMENT**
  - Cu/Gr COMPOSITE TO REPLACE Be FINS WITHOUT MASS PENALTY
- **HEAT PIPE/RADIATOR DESIGN CODES AND CORRELATION**
  - ANALYSIS, AUDITS, TRANSIENT BEHAVIOR
  - TESTING

JW91 02 7-pm

THERMAL MANAGEMENT
BASELINE BUDGET

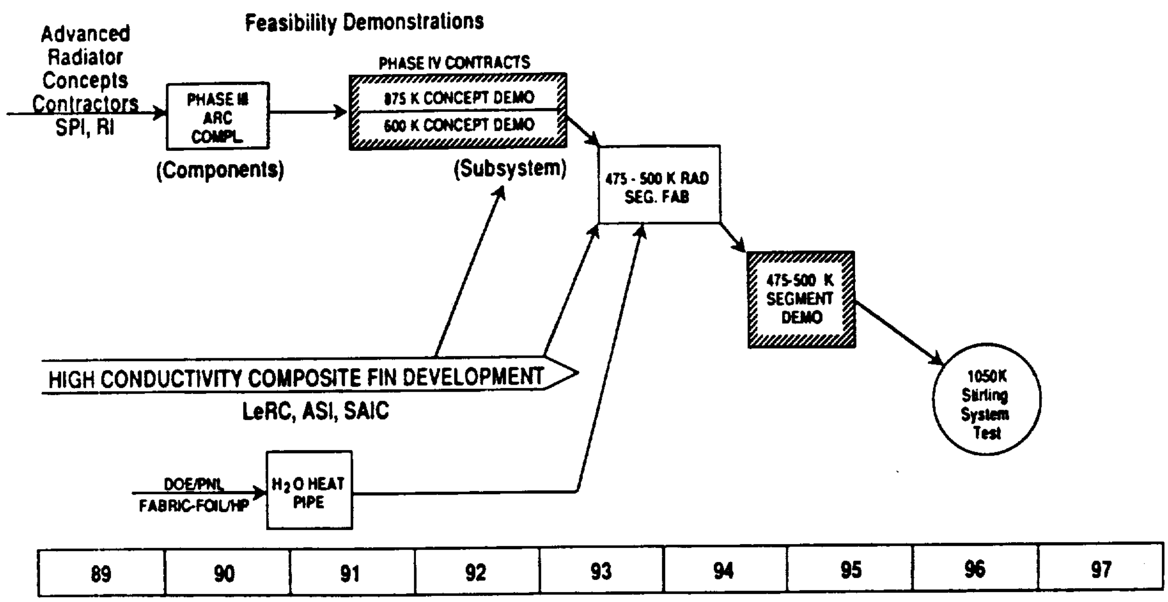
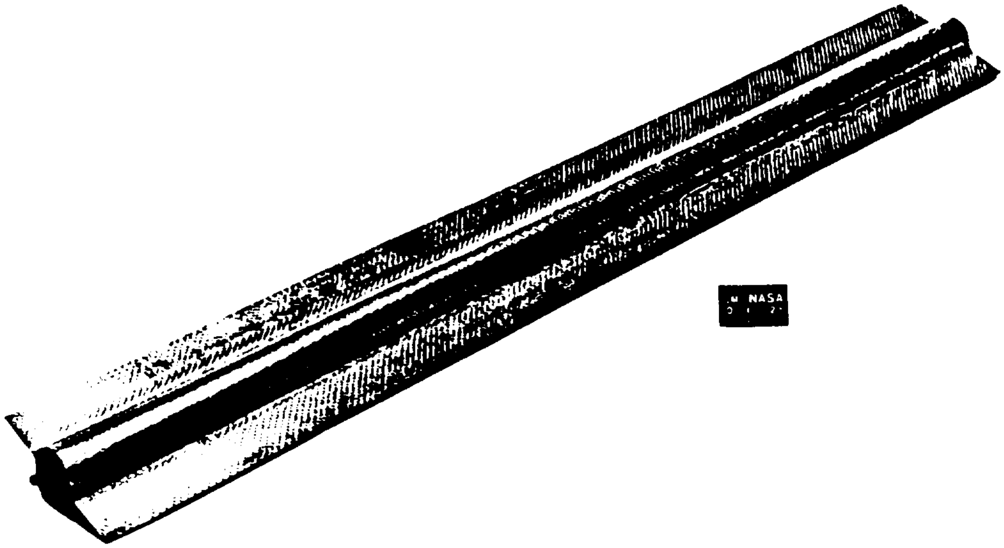


Figure 9

JMW90-004.4



HIGH CAPACITY POWER

NASA

ROCKWELL ACCOMPLISHMENTS

- DEMONSTRATED CARBON-CARBON COMPOSITE INTEGRATED TUBE-FIN MANUFACTURING TECHNOLOGY
- IDENTIFIED Nb AND Ti AS LINER OR COATING MATERIALS TO CONTAIN WORKING FLUID
- IDENTIFIED BRAZE MATERIALS AND Re PRECOAT FOR JOINING LINERS TO TUBES (PERFORMED INITIAL BRAZING AND COATING EXPERIMENTS)
- INITIATED TWO ALTERNATIVE METAL FOIL LINER FABRICATION SUBCONTRACTS

JW91.02 5-pm

SPI

LOW TMPERATURE Li-NaK RADIATOR EXPERIMENTAL TEST SECTION

Operated In Li-NaK Loop

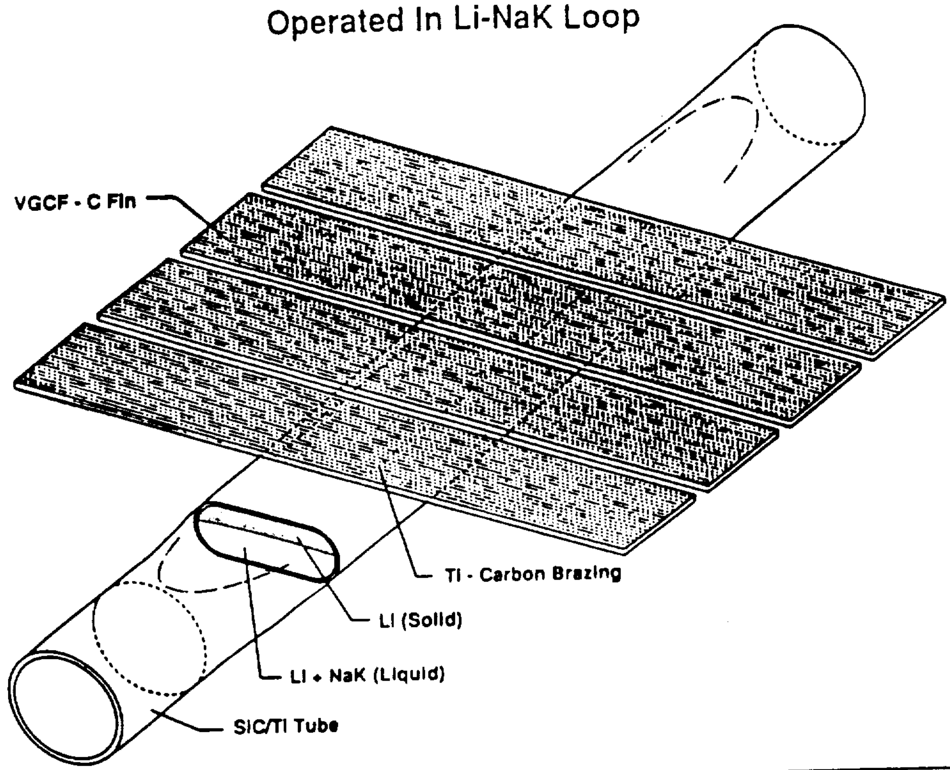


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FIGURE 1

HIGH CAPACITY POWER

NASA

SPI ACCOMPLISHMENTS

- COMPLETE Li/NaK LOOP GROUND TEST FACILITY
- PERFORMED Li/NaK FLOW TESTS IN BOTH Li THAW AND Li FREEZE MODES
- DEVELOPED 2-D COMPUTER SIMULATION OF Li/NaK FREEZE/THAW WITH VIDEO GRAPHIC OUTPUT
- PERFORMED LONG TERM (3000 hr) HIGH TEMPERATURE Li/NaK CAPSULE TS TO VERIFY MIXTURE STABILITY
- FABRICATED OIL-WATER FLOW VISUALIZATION LOOP SIMULATOR

JW91 02 4-pm

PNL ACCOMPLISHMENTS

- DESIGNED AND FABRICATED ULTRA-LIGHT HEAT PIPES WITH METAL FOIL LINERS AND HIGH STRENGTH WOVEN CERAMIC FIBER MANTLE

- TESTED FABRIC-FOIL HEAT PIPE WITH H_2O FLUID AND DELIVERED PROTOTYPE TO LeRC FOR MORE EXTENSIVE TESTING

JW91 02 6-pm

HIGH CAPACITY POWER

HEAT PIPE CODES

DEVELOPED STEADY STATE DESIGN CODE

- VALIDATED WITH SP-100 HEAT PIPE DATA
- INCORPORATED IN HEPSPARC RADIATOR DESIGN CODE
- IMPROVED VAPOR FLOW ALGORITHM
- WILL BE USED FOR HEAT PIPE DESIGN & AUDITS

TRANSIENT CODES

- JOINT EFFORT (NASA, AIR FORCE, WSU, UCLA, UNM)
- MODELS SP-100 HEAT PIPE START-UP FROM FROZEN STATE
- VAPOR FLOW REGIONS COMPLETED AND VALIDATED
- COMPLETED EXPERIMENTS FOR CODE VALIDATION

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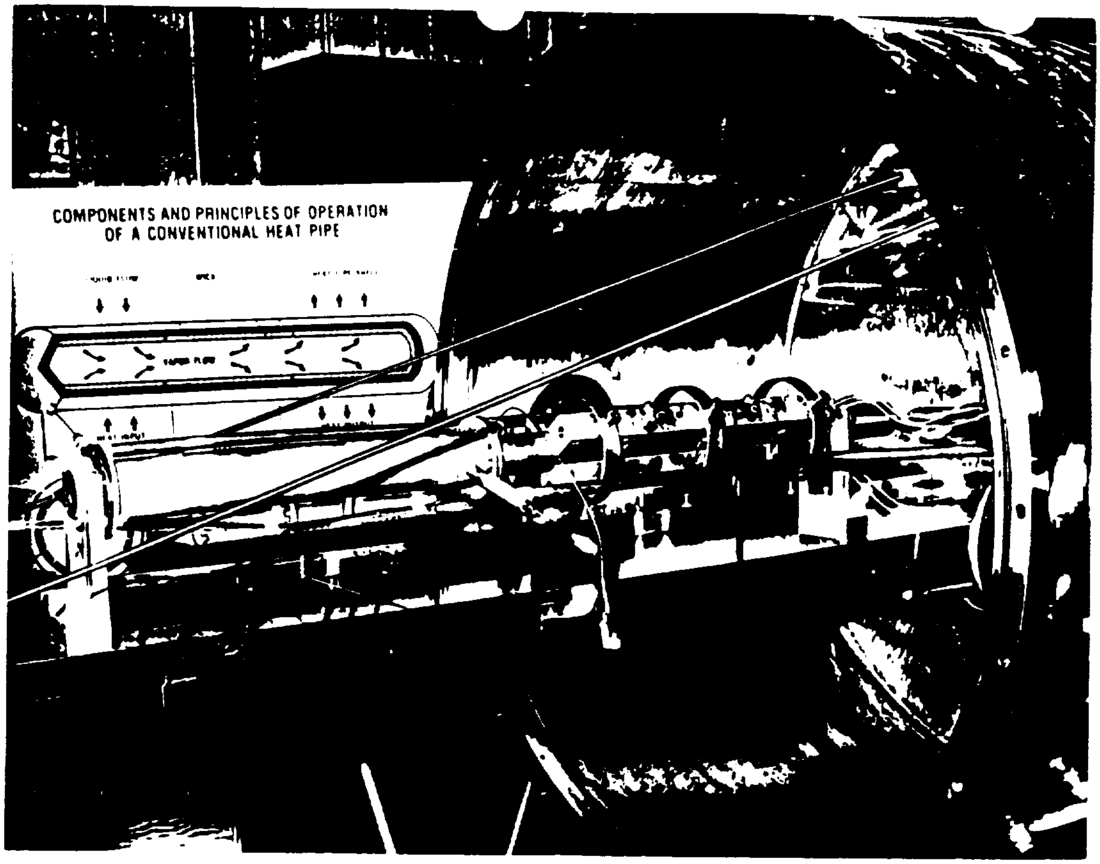

EXPLORATION TECHNOLOGY

HIGH CAPACITY POWER

NASA LeRC HEAT PIPE LABORATORY

- OPERATED WATER, LIQUID METAL HEAT PIPES
- FACILITY DATA ACQUISITION SYSTEM CHECK-OUT COMPLETE
- SIMULATE STIRLING AND THERMOELECTRIC RADIATOR OPERATING CONDITIONS
- INITIATING TESTS ON PNL FIBER-FABRIC HEAT PIPE
  - FUTURE TEST ON CONTRACTOR HEAT PIPES

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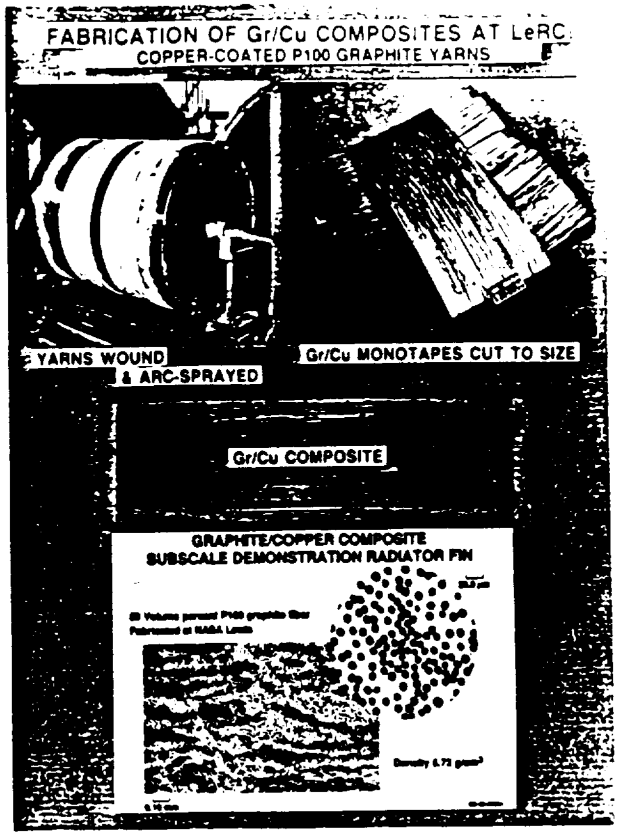

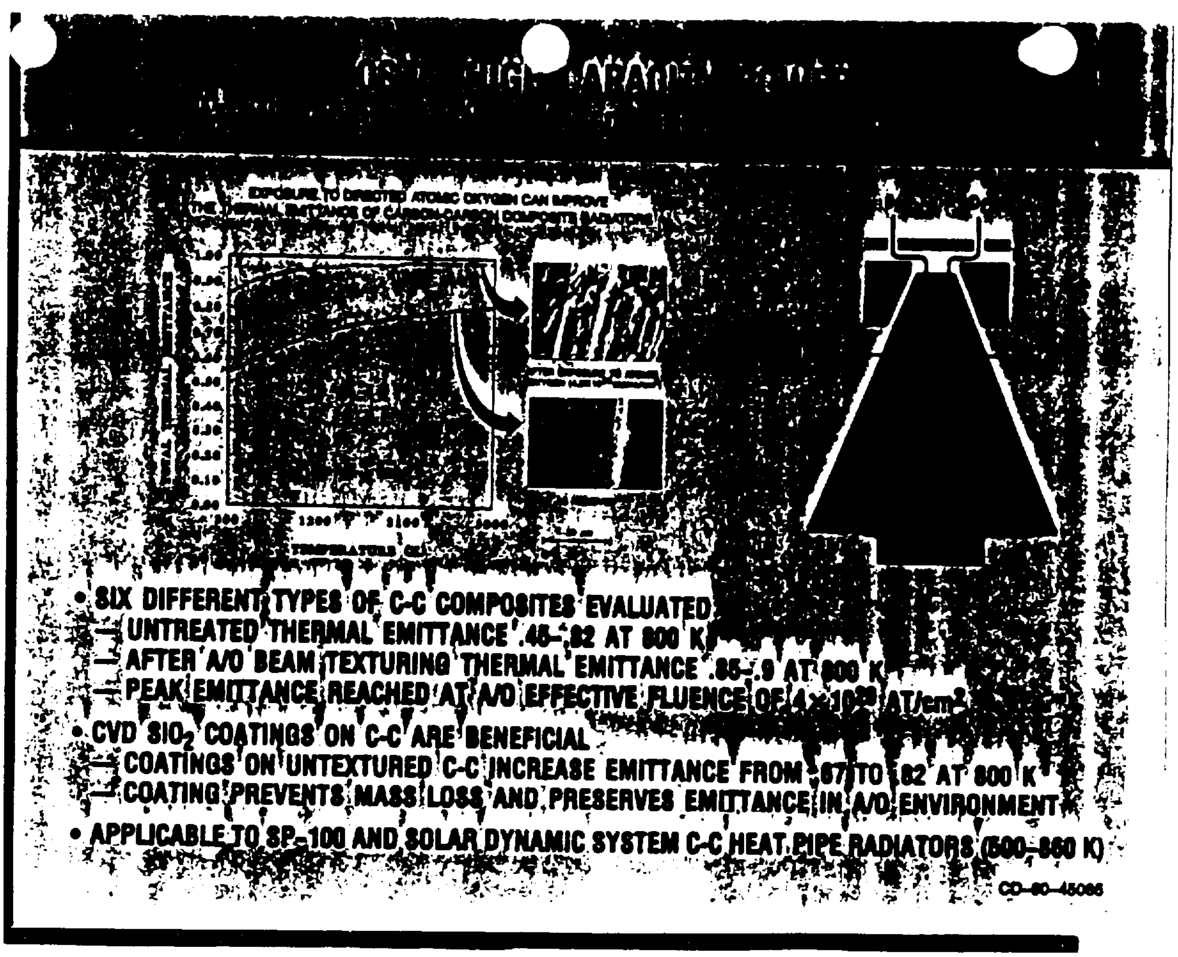

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ADVANCED MATERIALS

MAJOR OBJECTIVES:

DEVELOP MATERIALS WITH SIGNIFICANTLY ENHANCED CHARACTERISTICS COMPARED TO SOA RADIATOR AND REFRACTORY MATERIALS

- RADIATOR FIN MATERIALS TO REPLACE Be WITH NO MASS PENALTY
- REFRACTORY MATERIAL/COMPOSITE WITH FACTORS 2 TO 10 IMPROVEMENT IN CREEP STRENGTH COMPARED TO Nb-1Zr
- DEVELOP DATA BASE TO QUALIFY ALL MATERIALS AT DESIGN CONDITIONS (PWC-11, IN 718, IN 720, Cu/Gr, W/Nb, MoHfC/Nb)

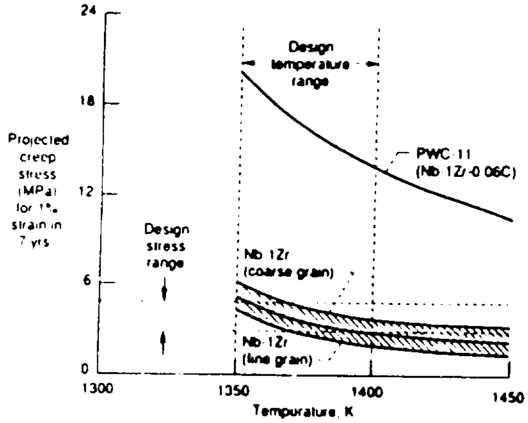
ITP.JMW91-001.6

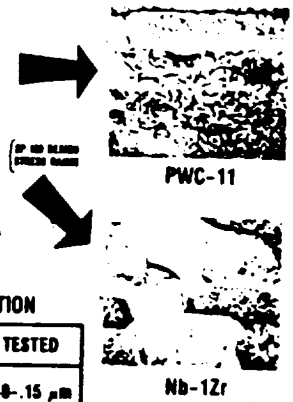
ADVANCED MATERIALS
MAJOR PROJECT ELEMENTS

- **DEVELOPMENT OF PWC-11**
  - SPECIFICATION, FABRICATION, TESTING, APPLICATION (WELDING/JOINING)
- **DEVELOPMENT OF WIRE REINFORCED REFRACTORY COMPOSITES**
  - WIRE CHARACTERIZATION, COMPOSITE FABRICATION, TESTING, APPLICATIONS
- **MATERIAL SELECTION AND COMPATIBILITY DETERMINATION FOR SUPERALLOY STIRLING DESIGNS AND REFRACTORY STIRLING DESIGNS**

JW91 02 3-pn

PWC-11 Alternate for Nb-1Zr





PWC-11 PRECIPITATE CHARACTERIZATION

	AS-ROLLED	HEAT TREATED	TESTED
SIZE	1-10 μm	.05-.10 μm	.10-.15 μm
STRUCTURE	hcp	fcc	fcc
COMPOSITION	Nb_2C	(Zr,Nb)C	(Zr,Nb)C

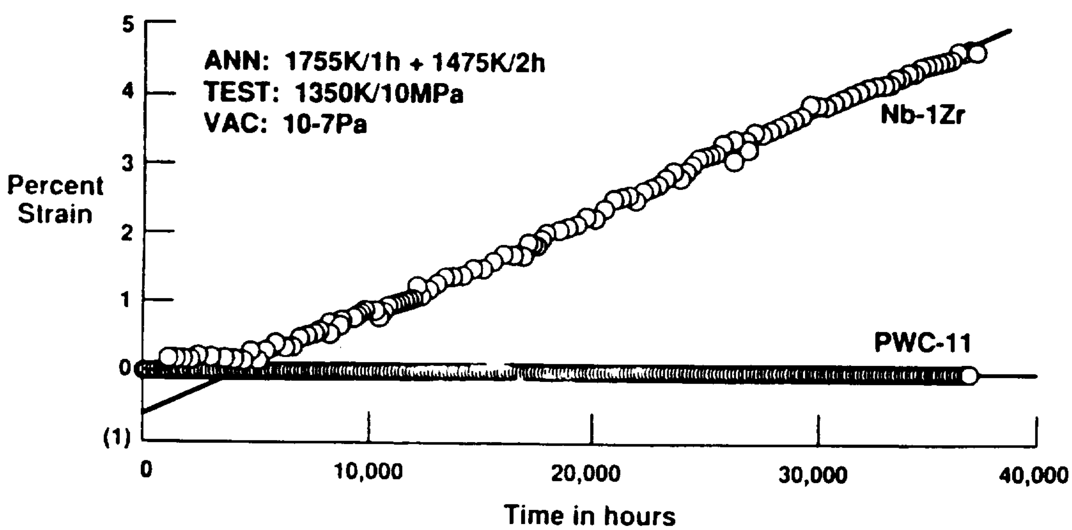
- Nb_2C TRANSFORMS TO STABLE (Zr,Nb)C PARTICLE
- AGING AT 1350-1400 K DOES NOT OVERAGE PRECIPITATE PARTICLE
- AFTER 35,000 h PRECIPITATE (Zr,Nb)C STILL EFFECTIVE STRENGTHENER

ATD AEROSPACE TECHNOLOGY DIRECTORATE

MATERIALS DIVISION

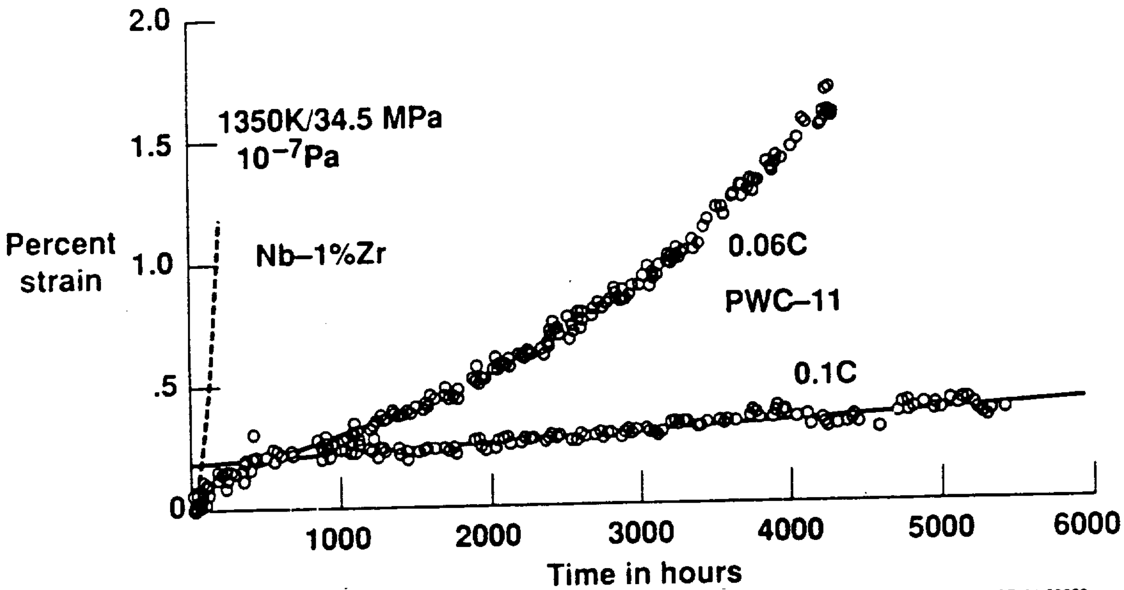
NASA Lewis Research Center

CREEP CURVES FOR Nb-1Zr & PWC-11 (0.06C)

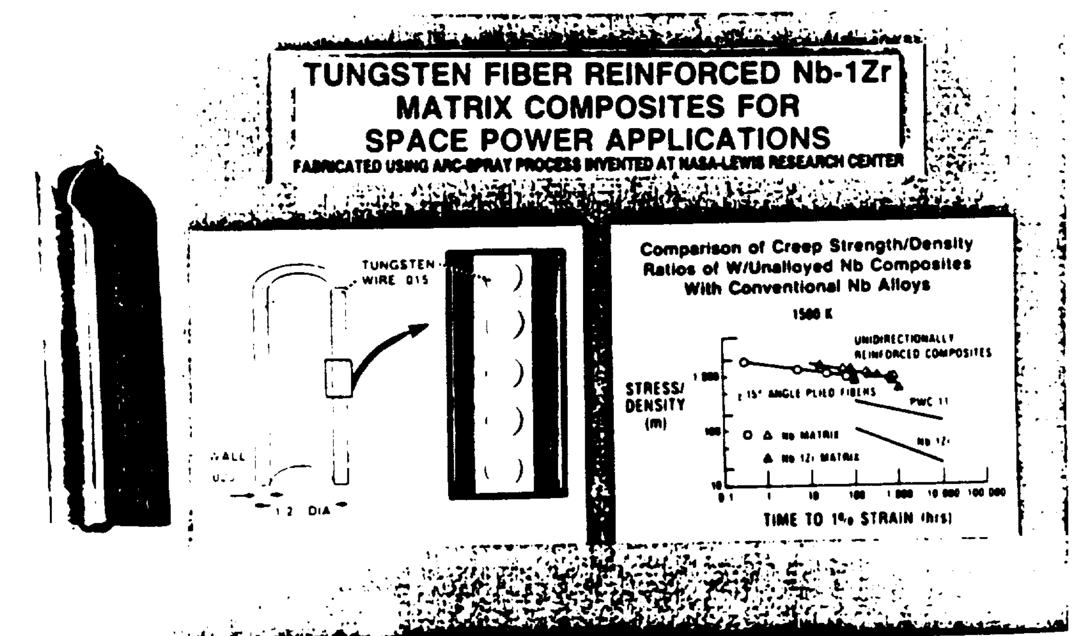


CD-90-51223

Creep Curves for Nb–1% Zr and PWC–11



CD-91-52652



HIGH CAPACITY POWER

NASA

REFRACTORY MATERIAL CANDIDATES FOR 1300K STIRLING

BASE MATERIAL	MP (K)	ρ (g/cc)	ALLOY NAME	COMPOSITION (wt%)	JOINABILITY	FABRICABILITY	ALLOY AVAILABILITY	DATA AVAILABILITY	VACUUM (torr)
W	3680	19.3	W-25Re-HfC	24-26% Re 1% HfC	5	4	4	3	10^{-6}
Ta	3270	16.6	ASTAR-811C	8% W 1% Re 1% HfC	8	8	10	5	10^{-8}
Mo	2880	10.2	TZM	0.08% Zr 0.5% Ti	2	8	10	4	10^{-6}
			TZC	1.25% Ti 0.1% Zr 0.15% C	2	6	10	4	10^{-6}
Mo/Re	2780	15.5	Mo-47.5 Re	47.5% Re bal Mo	8	6	8	3	10^{-6}
Nb	2740	8.6	FS-85	11% W 28% Ta 1% Zr	8	8	5	4	10^{-8}
			B-88	27% W 2% HfC	7	7	4	2	10^{-8}
			C-103	10% Hf 1% Ti 0.7% Zr	10	10	10	7	10^{-8}
			PWC-11	1% Zr 0.1% C	10	10	10	7	10^{-8}
			Nb-1Zr	1% Zr	10	10	10	8	10^{-8}

JED91-001 2

HIGH CAPACITY POWER

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POWER MANAGEMENT/SYSTEM DIAGNOSTICS

MAJOR OBJECTIVES:

DEVELOP PMAD ARCHITECTURE TO ENABLE USE OF FPSC's IN FUTURE MISSIONS

- CONTROL STABILITY, LOW MASS (1 kg/kWe), RELIABILITY (.99)

TEST POWER SWITCHES IN HIGH TEMPERATURE (425K), HIGH RADIATION (10^{13} n/cm, .5 Mrad gamma), ENVIRONMENTS

DEVELOP DIAGNOSTIC SENSORS AND SYSTEMS TO MONITOR NUCLEAR SYSTEM PERFORMANCE WITH EMI IMMUNITY AND SAFETY UNDER EXCESS CURRENT AND INSULATION BREAKDOWN CONDITIONS

ITP.JMW91-001.5

TECHNICAL HIGHLIGHTS

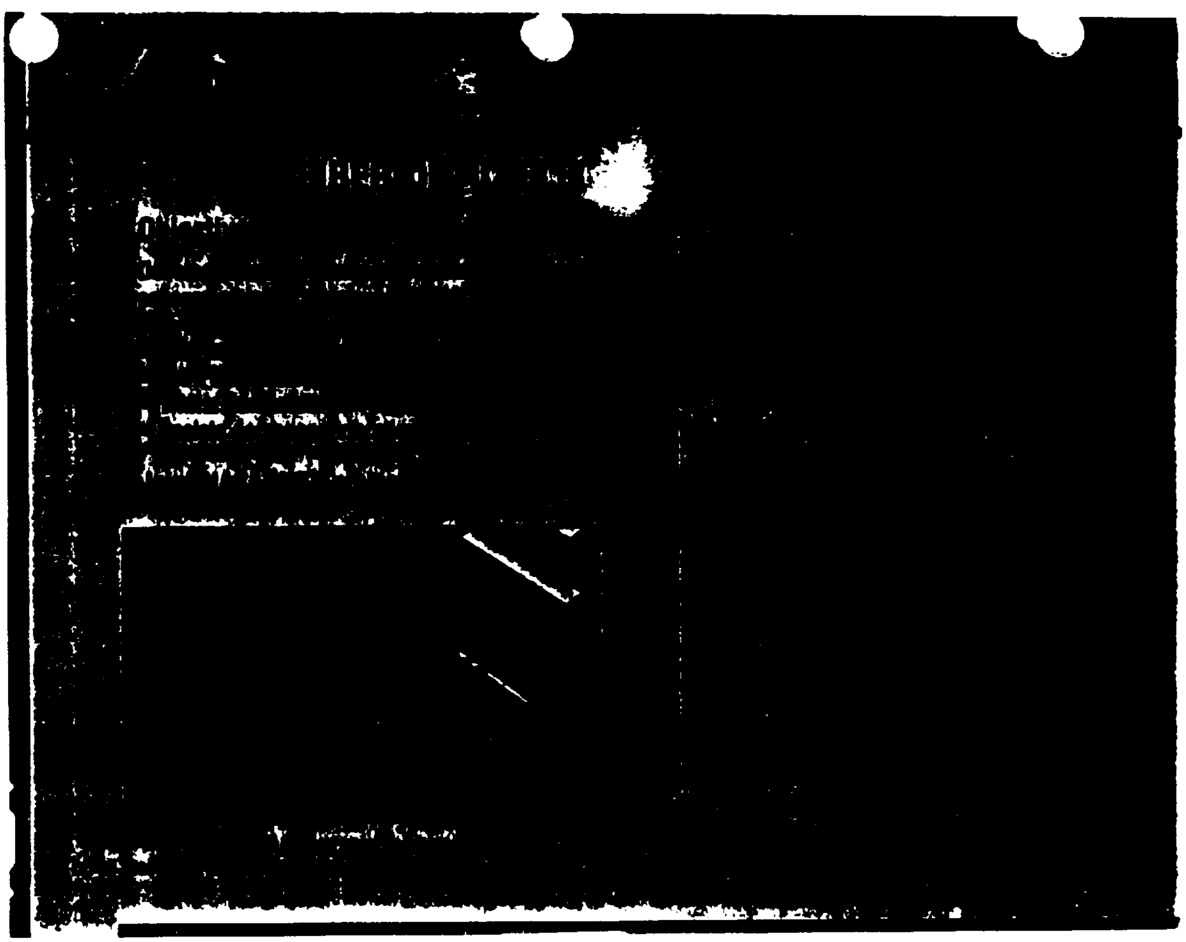
PMAD

- SET-UP TEST LABORATORY TO DEVELOP CONTROL TECHNIQUES FOR MULTIPLE FREE-PISTON STIRLING CONVERSION SYSTEMS
- QUALIFIED HIGH TEMPERATURE (525K) MAGNETIC MATERIALS FOR FPSE LINEAR ALTERNATOR - Sm_2Co_{17}
- IRRADIATED COMMERCIAL SEMI-CONDUCTOR POWER SWITCHES TO SP-100 SPECIFICATIONS - ALL DEGRADED
- BEGAN DEVELOPMENT OF SiC SWITCHES TO MEET REQUIREMENTS

SYSTEM DIAGNOSTICS

- FIBER OPTIC CURRENT SENSOR COMPLETE (IR&D 100 AWARD)
- FIBER OPTIC VOLTAGE SENSOR NEAR COMPLETION

ITP.JED91-001.4



SPACE ENVIRONMENTAL EFFECTS

MAJOR OBJECTIVES:

DEVELOP CODES AND EXPERIMENTAL CORRELATIONS TO PREDICT BEHAVIOR OF HIGH POWER SYSTEMS UNDER RELEVANT ENVIRONMENTS

- EPSAT CODE EXTENDED TO LUNAR AND MARS ENVIRONMENTS (Atomic Oxygen, Meteoroids, Space Plasma, Ion Effluents)

ENSURE SAFETY AND LONG-LIFE OPERATION OF HIGH POWER SYSTEMS

ITP JMW91-001.7

HIGH CAPACITY POWER

NASA

TECHNICAL HIGHLIGHTS - ENVIRONMENTAL EFFECTS

- MEASURED ATOMIC OXYGEN IONIZED SPUTTERING YIELDS TO CORRELATE WITH SP-100 MATERIALS AND DESIGNS
- MEASURED AND MODELED CURRENTS THROUGH CABLE INSULATION PINHOLES
- MEASURED DIELECTRIC BREAKDOWN POTENTIAL BETWEEN SPACE PLASMA AND SPACECRAFT

ITP.JED91-001.5

FULL-UP/AUGMENTED PROGRAMS

JW91 02 2-pm

BUDGETS, $ M

YEAR	BASELINE	AUGMENTED	FULL-UP
1991	10.4	10.4	10.4
1992	10.6	10.6	10.6
1993	4.5	10.9	11.1
1994	4.6	12.0	16.8
1995	4.8	12.3	23.0
1996	5.0	12.6	30.5
1997	5.2	18.0	23.0

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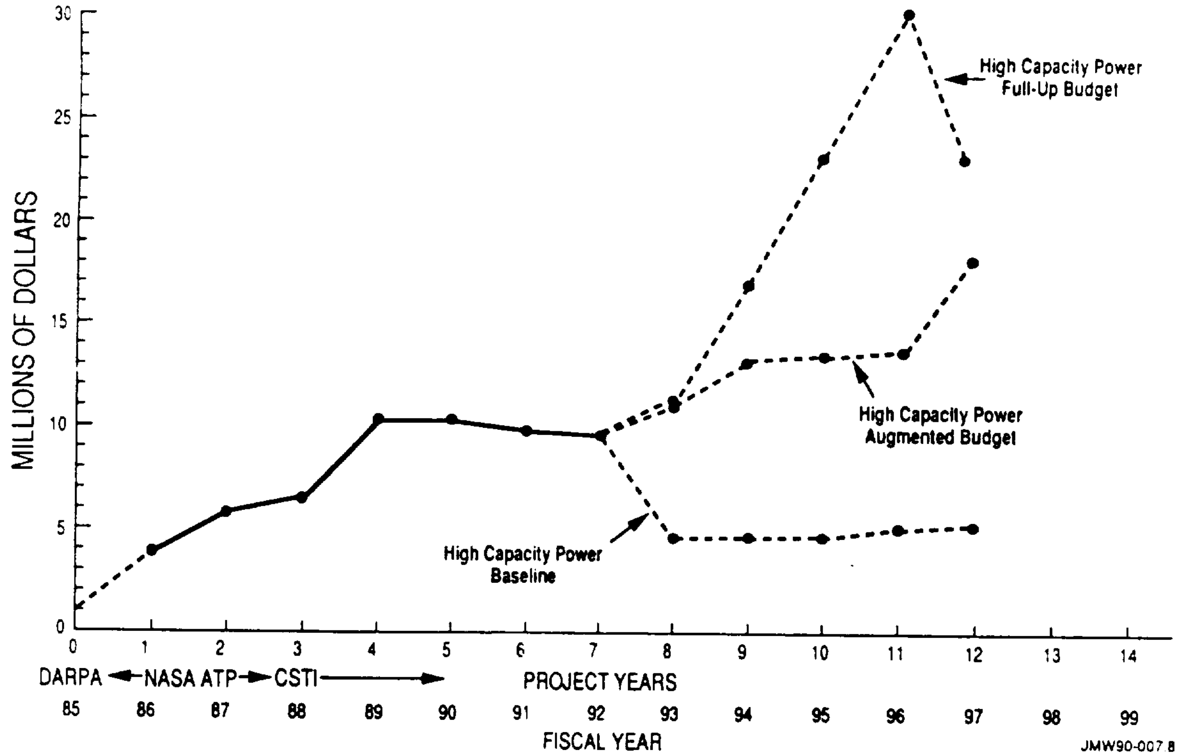
HIGH CAPACITY POWER

NASA

GROSS FUNDING HISTORY/PROJECTIONS
NASA SP-100 ATP - HIGH CAPACITY POWER



EXPLORATION TECHNOLOGY

SURFACE SYSTEMS/OPERATIONS

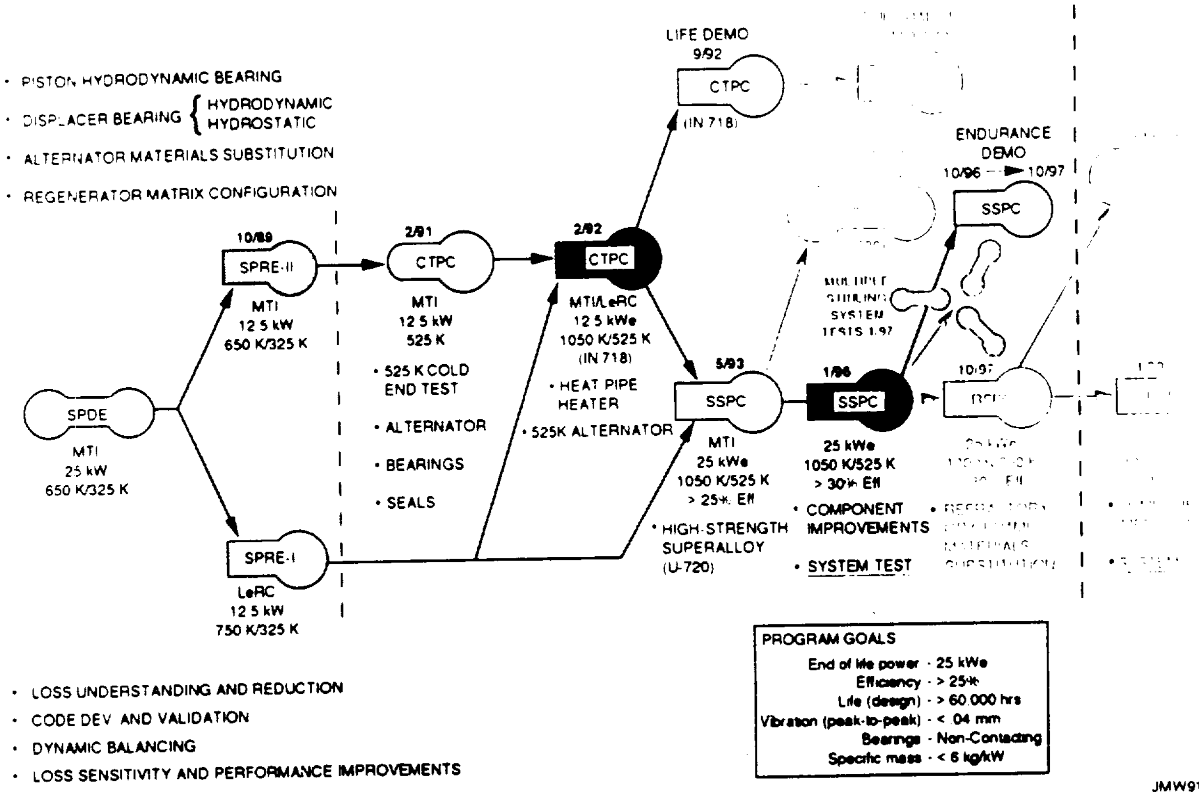
OAET

CURRENT PROGRAM

- 1050K SUPERALLOY STIRLING DEMONSTRATION- 25% EFF., 6 kg/kWe, 25 kWe - 1994
  - 30% IN 1996
  - 1 YEAR OPERATION IN 1997
- 450K WATER HEAT PIPE DEMONSTRATION < 5kg/m^2 - 1992
  - 525K RADIATOR SEGMENT DEMO IN 1994
- THERMOELECTRIC MATERIAL (SiGe/GaP) Z = 1.0 X 10^{-3} K^{-1} DEMONSTRATED - 1994
- RADIATION HARD CIRCUITS DEVELOPED - 1995
- OPTIC POWER SENSING SYSTEM DEVELOPED - 1995
- ATOMIC OXYGEN, CO_2 ION, AND CO TESTING OF MATERIALS FOR MARTIAN SURFACE - 1997

ITP.JMW91-001.8

STIRLING DEVELOPMENT
FULL-UP BUDGET



EXPLORATION TECHNOLOGY

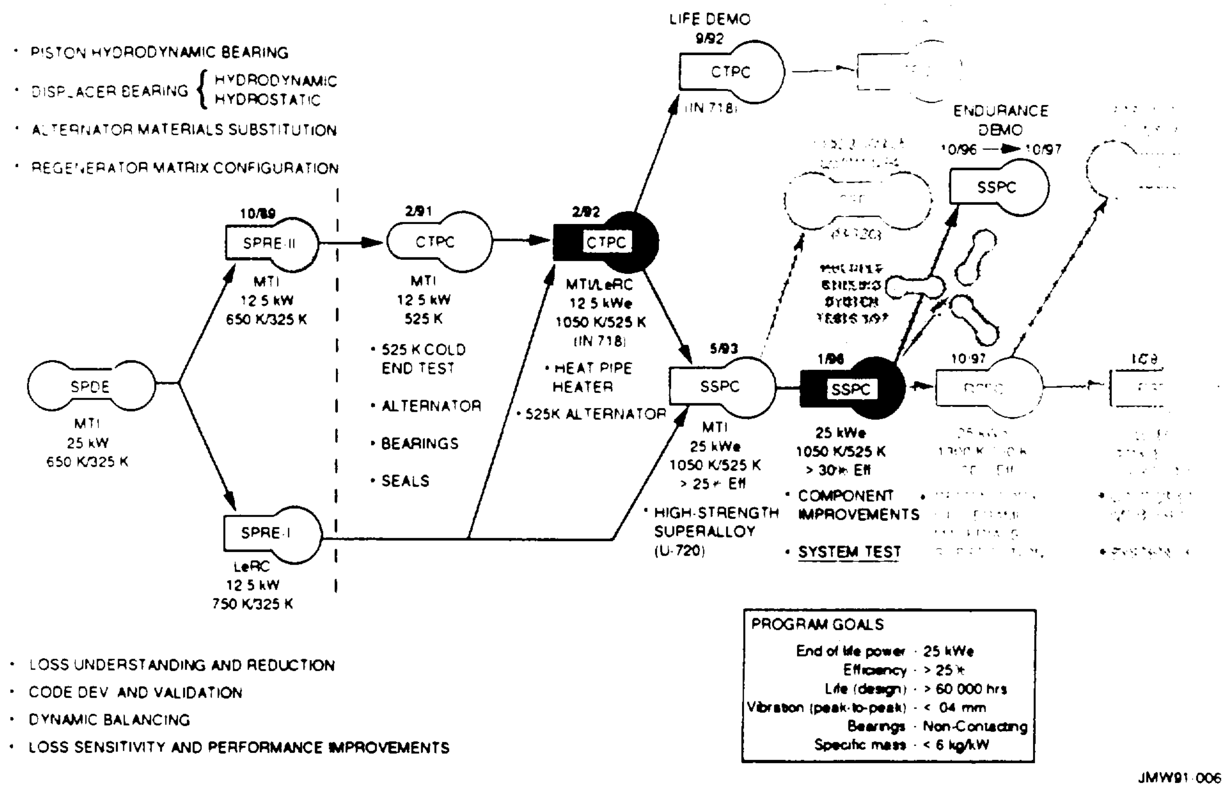
HIGH CAPACITY POWER

FULL-UP BUDGET PROGRAM

- **FULL-UP PROGRAM CONTAINS ALL ELEMENTS AND CoF NECESSARY TO COMPLETE A 1300K FREE-PISTON STIRLING TEST IN 1997, PROVIDES SIGNIFICANT PROGRESS IN RADIATORS, MATERIALS, PMAD, ENVIRONMENTAL INTERACTIONS**
  - 30% EFFICIENCY, 6 kg/kWe, 25 kWe REFRACTORY POWER CONVERTER
  - MULTIPLE STIRLING SYSTEM TESTS FOR POWER SYSTEM PHASING AND CONTROL
  - 5 kg/m2, 600K RADIATOR
  - FACILITIES TO PERFORM POWER CONVERSION/RADIATOR SYSTEM TESTS
  - ENDURANCE TESTS AND ACCELERATED LIFETIME MODELS/TECHNIQUES TO ASSURE 10 - 15 YEAR LIFE
  - 875K RADIATOR SEGMENT TESTS FOR THERMOELECTRICS
  - MATERIALS DATA BASE AND APPLICATION OF SUPERALLOYS, PWC-11, REFRACTORY COMPOSITES AND RADIATOR MATERIALS TO SYSTEM TESTS
- **ALL OF THE DESIGNS, THE FACILITIES, AND MOST OF THE HARDWARE WILL BE IN PLACE AT THE END OF 1997 TO SUPPORT THE REFRACTORY STIRLING POWER CONVERTER SYSTEM TEST IN 1999 AND THE ENDURANCE TEST IN 2000**

ITP RJS91-001.7

STIRLING DEVELOPMENT
AUGMENTED BUDGET



EXPLORATION TECHNOLOGY

HIGH CAPACITY POWER

Δ AUGMENTED PROGRAM

ELIMINATES THE FOLLOWING:

- HARDWARE AND FACILITIES FOR 1300K STIRLING SYSTEM TEST
- DOUBLE-ENDED STIRLING ENDURANCE TESTS AT 1050K AND 1300K
- MULTIPLE STIRLING SYSTEM TEST
- BASIC UNDERSTANDING, CODE DEVELOPMENT AND CORRELATION TO REDUCE PROGRAM RISK
- THERMAL MANAGEMENT DEVELOPMENT FOR 1300K STIRLING SYSTEM TEST
- ADVANCED PMAD AND DIAGNOSTIC FULL SYSTEM DEVELOPMENT
- MODELLING DEVELOPMENT FOR LUNAR AND MARS ENVIRONMENTS, ION THRUSTER EFFLUENTS
- DETAILED MATERIAL DATA BASE AND APPLICATION DEVELOPMENT FOR ADVANCED ALLOYS AND COMPOSITES
- FACILITY DEVELOPMENT FOR REFRACTORY TESTING AT SIMULATED MARS CONDITIONS

ITP.RJS91-001.14

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THERMAL MANAGEMENT
BASELINE BUDGET

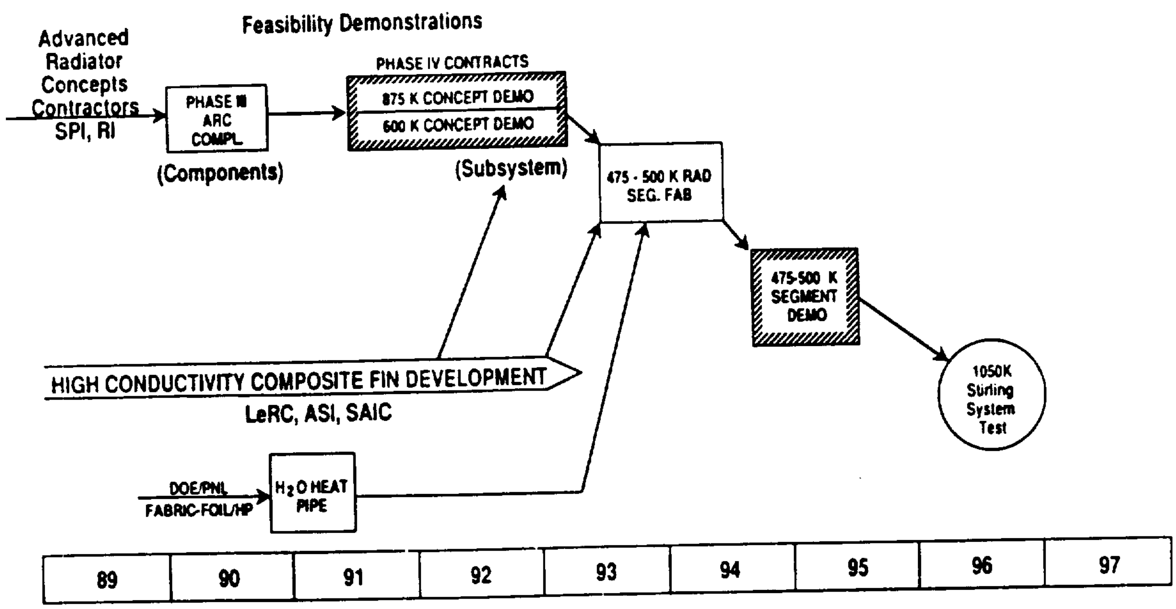
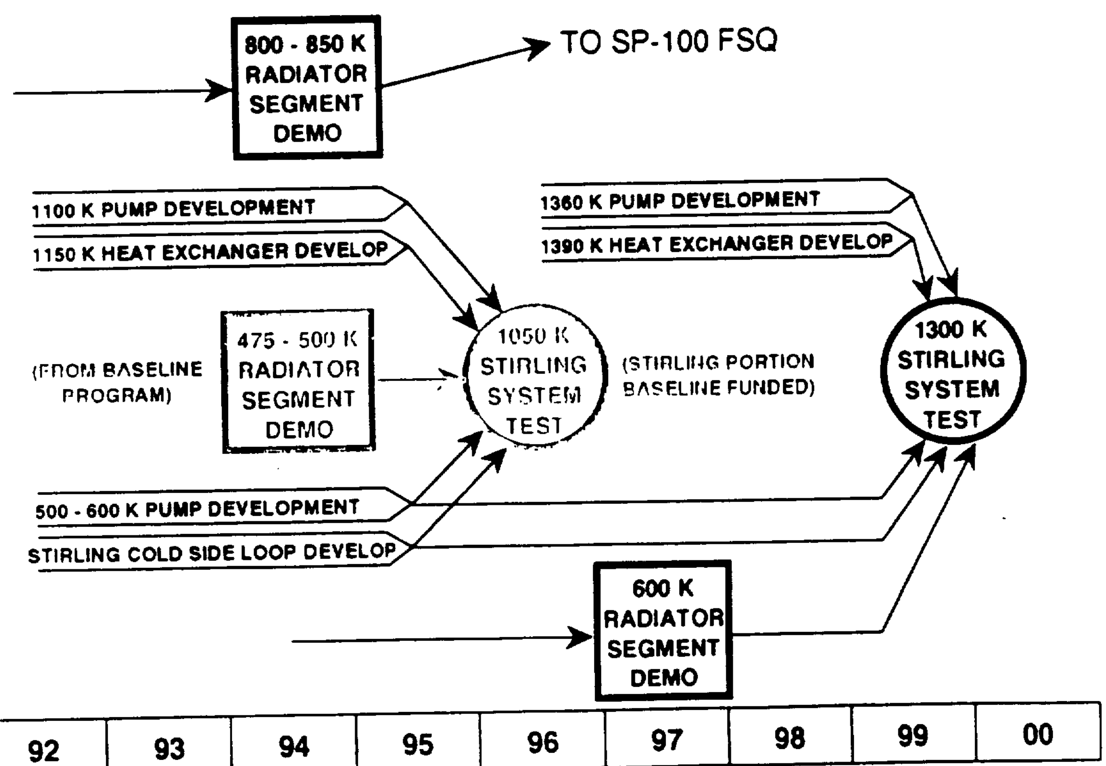


Figure 9

JMW90-004.4

THERMAL MANAGEMENT
FULL-UP BUDGET



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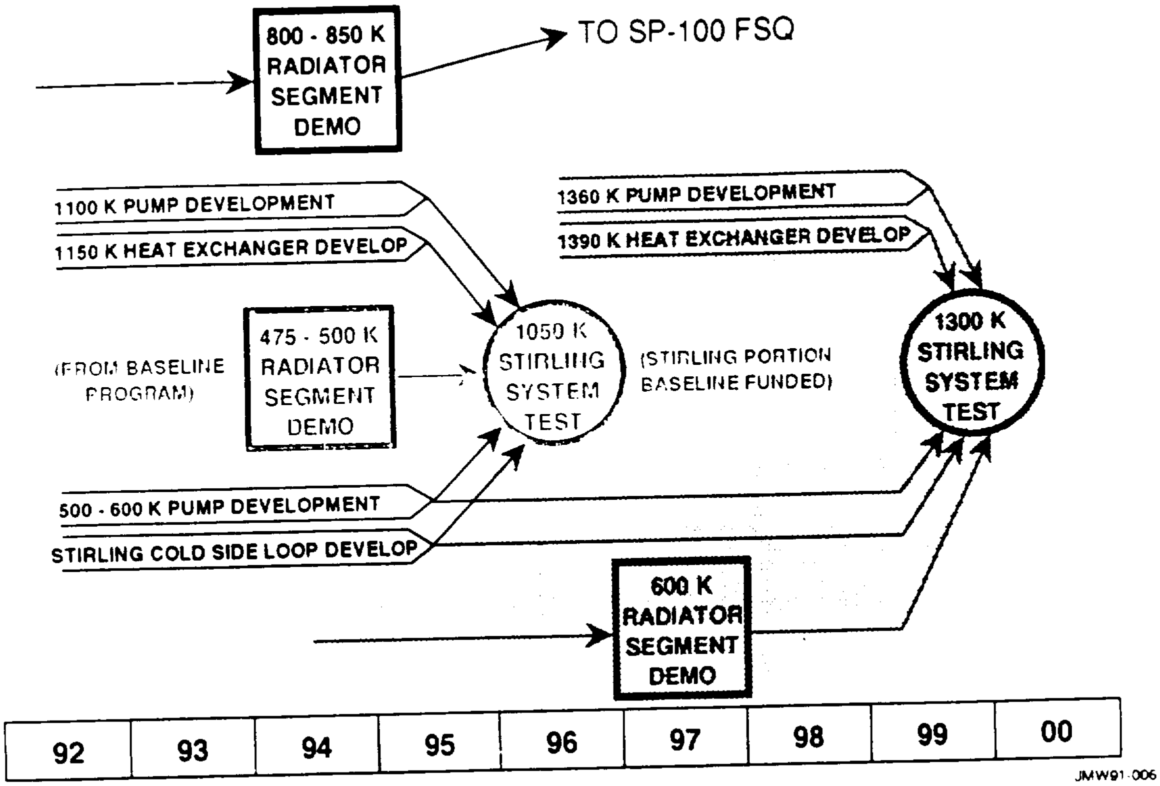
THERMAL MANAGEMENT AUGMENTED BUDGET



EXPLORATION TECHNOLOGY

HIGH CAPACITY POWER

PMAD/SYSTEM DIAGNOSTICS

FULL-UP BUDGET

PMAD
- RADIATION-HARD CIRCUITS DEVELOPED AND DEMONSTRATED AT SYSTEM OPERATING CONDITIONS
- SOFT MAGNETIC MATERIALS COMPLETELY CHARACTERIZED FOR USE IN HIGH POWER, HIGH TEMPERATURE, SPACE POWER APPLICATIONS
  - COMPONENTS (TRANSFORMERS) DESIGNED AND TESTED IN RELEVANT ENVIRONMENTS

DIAGNOSTICS
- DEVELOP EXTENDED RANGE OF OPERATION FOR POWER SENSORS (TEMPERATURE AND VIBRATION)
- SENSORS MODIFIED FOR PRODUCTION / THEN FLIGHT QUALIFIED

ITP.RJS91-001.15

HIGH CAPACITY POWER

PMAD/SYSTEM DIAGNOSTICS

AUGMENTED BUDGET

PMAD
- RADIATION-HARD DEVELOPMENTS RESTRICTED TO SWITCHES, NOT CIRCUITS
- LESS SOFT MAGNETIC MATERIALS CHARACTERIZED, NO COMPONENTS TESTED

DIAGNOSTICS
- RESTRICTED RANGE OF TEMPERATURE AND VIBRATION OPERATION
- MAY NOT FULLY QUALIFY FOR FLIGHT, NOT PRODUCTION ITEMS

ITP RJS91-001.16

HIGH CAPACITY POWER

NASA

ENVIRONMENTAL INTERACTIONS

BASELINE
- ATOMIC OXYGEN, CO_2 ION, AND CO TESTING OF POWER SYSTEM MATERIALS FOR MARTIAN SURFACE APPLICATIONS

AUGMENTATION
- TESTING FOR PASCHEN BREAKDOWN OF HIGH VOLTAGE POWER SYSTEM GEOMETRIES IN LUNAR AND MARTIAN LOCAL ATMOSPHERIC CONDITIONS (AND DUST)

FULL-UP
- EPSAT - BASED MODELLING OF POWER SYSTEM INTERACTIONS WITH ION THRUSTER EFFLUENTS, ETC.
- MODEL/CORRELATION OF SYSTEM BEHAVIOR FOR LUNAR AND MARTIAN ENVIRONMENTS

JW91.02.1-pm

RELATED EFFORTS

- JPL BASE R&T EFFORT ON SILICIDE THERMOELECTRICS WITH POTENTIAL ORDER OF MAGNITUDE IMPROVEMENT IN Z
- DOE SOLAR STIRLING DEVELOPMENT - 1050K, 25 kWe/CYLINDER
- GE SP-100 CONTRACT FOR THERMOELECTRIC MODULES (Z = .85) AND SPACE RADIATORS
- DOD DEVELOPMENT OF SURVIVABLE SPACE RADIATOR TECHNOLOGY
  - CODE DEVELOPMENT
- DOD DEVELOPMENT OF RADIATION HARD SENSOR TECHNOLOGY
- DOD DEVELOPMENT OF EARTH ORBITAL ENVIRONMENTAL INTERACTIONS MODELS/EXPERIMENTS - EPSAT

ITP RJS91-001.9

FOCUSED TECHNOLOGY: HIGH CAPACITY POWER
SUMMARY

- IMPACT:
  - Advanced conversion (Stirling/Thermoelectric) coupled to an SP-100 reactor will provide the enabling technology for the development of lunar and Mars surface power systems
- USER COORDINATION:
  - SEI technology requirement for Surface Systems and NEP being developed co-operatively with RP, RZ, JSC PSS - - High Priority in RZ
  - Planetary science requirements being developed with OSSA and with JPL
- OVERALL TECHNICAL AND PROGRAMMATIC STATUS:
  - Significant progress in all areas including Conversion Systems, Thermal Management, PMAD, Space Environment, and Materials Development
  - Stirling cold end component test successful at 525 K
  - Some program elements have been delayed by complex component fabrication issues and subscale feasibility test delays - - major out-year milestones not yet delayed
- MAJOR TECHNICAL/PROGRAMMATIC ISSUES
  - Lack of clear user commitment has delayed nuclear heat source development
  - Development/qualification of seven-year lifetime systems and technology to facilitate fifteen to twenty year overall lifetime

JMW91-005.4

HIGH CAPACITY POWER

CONCLUDING REMARKS

- HIGH CAPACITY POWER
  - BROAD-BASED PROGRAM
  - KEY ELEMENTS
  - SIGNIFICANT PROGRESS TO DATE
- CURRENT PROGRAM MEETS MANY KEY MILESTONES
- STRATEGIC PROGRAM NECESSARY TO BRING ALL PROGRAM ELEMENTS TO FRUITION
- AUGMENTED PROGRAM PROVIDES EARLY 1050K STIRLING ENDURANCE TEST, PLUS DESIGN, FAB, AND TEST OF A 1300K REFRACTORY STIRLING AND SELECTED CRITICAL SUBSYSTEMS

ITP.RJS91-001.11

SURFACE POWER
AND
THERMAL MANAGEMENT

BY

JOHN M. BOZEK
NASA LEWIS RESEARCH CENTER

ITP EXTERNAL REVIEW

JUNE 27, 1991

ITP JMB91-002.1

EXPLORATION TECHNOLOGY

Surface Power and Thermal Management

OBJECTIVES

- Programmatic
  Develop Solar-Based Power and Low-Grade Heat Thermal Management Technologies to Support Lunar and Mars Surface System Operations
- Technical

Power System	- 25 kWe @ 3 We/kg (Lunar), 8 We/kg (Mars)
Fuel Cell Life	- 20,000 hrs operational life
RFC Energy Density	- 500 to 1000 W-hr/kg
Thermal Ops.	- 60K to 400K with Long Life
Photovoltaics	- ≥ 300 W/kg (AMO)
Electrical	- ≤ 55 kg/kWe

SCHEDULE

- 1993 Select RFC PEM Membrane(s)
- 1994 Complete Thermal Model for RFC
- 1995 Full Area Fuel Cell
  PV Cell Choice
  50% Improvement in Cryo Heat Pipes
- 1996 300% Heat Pump Improvement
  Stable Electrical Transmission
  Fuel Cell Stacks Fabricated
- 1997 5,000 hrs on Fuel Cell Stack w/SOA Electrolyzer
  PV Cell/Blk/Structure Integrated
- 1998 1 yr Life Test on EPM Bread-Board
  Ground Verification of RFC/TPM
  TPM Flight Experiment Design
- 1999 Complete RFC B-B Test (Adv. FL/EL/Tanks)
- 2000 Bread-Board Performance of TD&C
  3 W/kg, 20,000 hr Lunar Power System Reference Design

RESOURCES

	CURRENT	"3X"	STRATEGIC
• 1991	$ 0.6 M	$ 0.6 M	$ 0.6 M
• 1992	$ 0 M	$ 0 M	$ 0 M
• 1993	$ 0 M	$ 3.4 M	$ 5.0 M
• 1994	$ 0 M	$ 9.0 M	$ 11.7 M
• 1995	$ 0 M	$12.6 M	$ 18.5 M
• 1996	$ 0 M	$14.0 M	$ 24.2 M
• 1997	$ 0 M	$18.0 M	$ 25.3 M
• BTC	$ 0 M	$ 9.0 M	$ 35.0 M

POTENTIAL PARTICIPANTS

- **Lewis Research Center**
  Lead; Analysis, Energy Storage, EPM, Thermal Mgt., PV
- **Jet Propulsion Laboratory**
  Supporting PV Arrays, Energy Storage, Analysis, Thermal Mgt.
- **Johnson Space Center**
  Supporting Energy Storage & Thermal Mgt.
- **Goddard Space Flight Center**
  Supporting Low-Temperature Thermal Mgt.
- **Los Alamos National Laboratory**
  Supporting Energy Storage Component Testing

ITP JMB91-002.2

SURFACE POWER AND THERMAL MANAGEMENT

WHAT IS IT ?

FOCUSED TECHNOLOGY PROJECT (ELEMENT OF EXPLORATION TECHNOLOGY PROGRAM)

- FOCUSED ON EXTRATERRESTRIAL SURFACES (LUNAR & MARS)
  - FOCUSED ON SOLAR-BASED POWER (REGENERATIVE)
    - FOCUSED ON ENERGY STORAGE (REGENERATIVE FUEL CELLS)
    - FOCUSED ON POWER GENERATION (PHOTOVOLTAICS)
    - FOCUSED ON ELECTRICAL POWER MANAGEMENT (TEMP.& POWER)
    - FOCUSED ON THERMAL POWER MANAGEMENT (3 R'S)

FOCUSED HARDWARE THAT IS SCALABLE TO NEEDS (TEST BEDS)

ITP.JMB91-002.17

SURFACE POWER AND THERMAL MANAGEMENT

PROJECT SUPPORTS EXPLORATION PROGRAM

THRU

FOCUSED TECHNOLOGY VERIFICATION

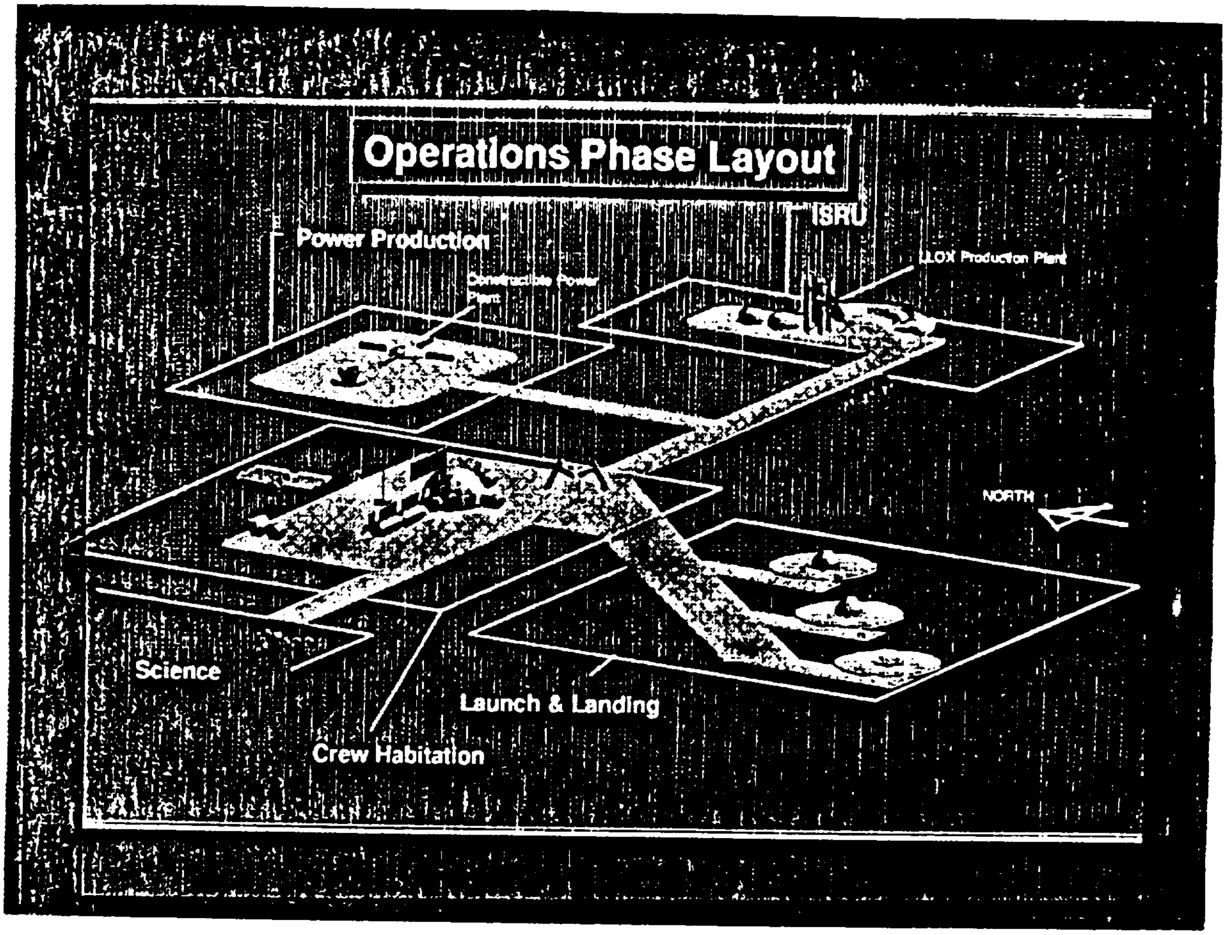
OF

ALL SOLAR-BASED POWER SYSTEM TECHNOLOGIES

AND

LOW-GRADE THERMAL MANAGEMENT TECHNOLOGIES

ITP.JMB91-002.3



EXPLORATION TECHNOLOGY

SURFACE POWER AND THERMAL MANAGEMENT

OBJECTIVE

DEVELOP SOLAR-BASED POWER AND THERMAL MANAGEMENT TECHNOLOGY TO A LEVEL OF READINESS SUFFICIENT TO ENABLE OR ENHANCE EXTRATERRESTRIAL SURFACE MISSIONS IN THE 21st CENTURY

ITP JMB91-002 7

SURFACE POWER AND THERMAL MANAGEMENT

GOALS

POWER SYSTEM

0.1 W/kg $\xrightarrow{\text{LUNAR}}$ 3 W/kg

2.0 W/kg $\xrightarrow{\text{MARS}}$ 8 W/kg

30 to 90 DAYS $\xrightarrow[\text{LIFE}]{\text{LUNAR/MARS}}$ UP to 5 YEARS

THERMAL MANAGEMENT

21 kg/kWT $\xrightarrow[\text{HEAT PUMPS}]{\text{LUNAR}}$ 7 kg/kWT

6 kg/WT $\xrightarrow[\text{160 K HEAT PIPES}]{}$ 0.3 kg/Wt

17 kg/WT $\xrightarrow[\text{80 K HEAT PIPES}]{}$ 5 kg/Wt

$\xrightarrow[\text{400 K}]{}$
- SIPHONS
- STORAGE
- HEAT PIPES, PUMPS
- OTHER

ITP.JMB91-002.8

SURFACE POWER AND THERMAL MANAGEMENT

TECHNOLOGY CHALLENGE

- COMPATIBLE TECHNOLOGIES FOR INTEGRATED SYSTEM
- LONG LIFE RFC WITHOUT SACRIFICING PERFORMANCE
- HIGH POWER DENSITY, ROBUST PHOTOVOLTAICS
- LOW MASS, RELIABLE, ENVIRONMENTALLY COMPATIBLE ELECTRICAL SUBSYSTEM
- LOW MASS, LONG LIFE, HIGH PERFORMANCE THERMAL REJECTION, RETENTION, AND REDISTRIBUTION

ITP.JMB91-002.11

SURFACE POWER AND THERMAL MANAGEMENT

STRATEGIC PROGRAM ELEMENT

- SYSTEM INTEGRATION
  - TRADE STUDIES: INNOVATIVE TECHNOLOGY FEASIBILITY
  - REFERENCE DESIGNS [3 W/kg (Lunar); 8 W/kg (Mars)]
- ENERGY STORAGE (RFC's)
  - FUEL CELLS [Life/Efficiency]
  - ELECTROLYZERS [Life/Efficiency]
  - REACTANT STORAGE [Life/Mass/Volume]
  - TEST BEDDED SUBSYSTEM [Life/Performance]
- POWER GENERATION (PV's)
  - CELLS [Life/Efficiency]
  - BLANKET [Mass]
  - STRUCTURE [Deployment]
  - SCALABLE ARRAY PERFORMANCE [AMO/Vacuum/Thermal]
- ELECTRICAL MANAGEMENT
  - INTEGRATION OF POWER SUBSYSTEMS [Mass, Temp., Efficiency, Reliability]
  - TRANSMISSION, DISTRIBUTION AND CONTROL [Mass, Temp., Autonomy, Environment]
  - TEST BEDDED SUBSYSTEM
- THERMAL MANAGEMENT
  - MODELING [Requirements]
  - COMPONENTS [Rejection, Retention, Redistribution]
  - TEST BEDDED SUBSYSTEM [RFC, EPM/TD&C, Science]
  - FLIGHT EXPERIMENT WHERE NECESSARY

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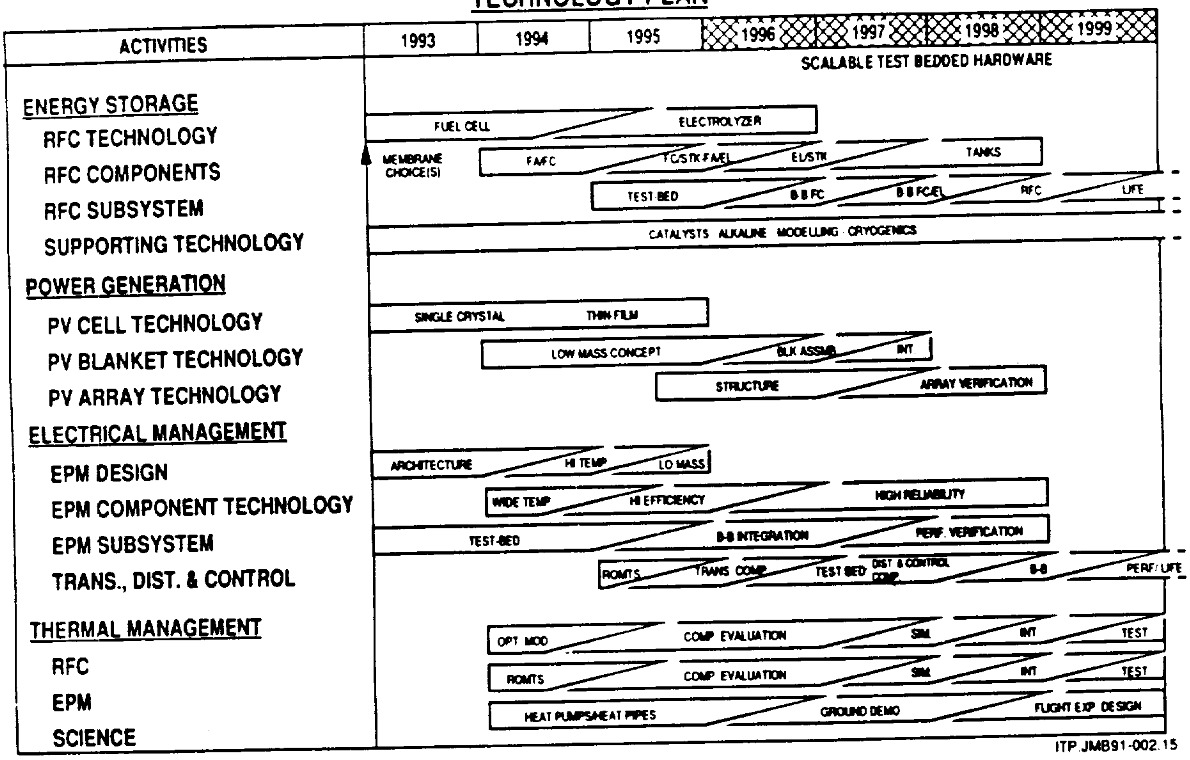
SURFACE POWER AND THERMAL MANAGEMENT

TECHNOLOGY PLAN



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SURFACE POWER AND THERMAL MANAGEMENT

SUMMARY

IMPACT:

- PROVIDES FOR EARLY DEPLOYMENT OF NEEDED POWER FOR LUNAR BASE
- MEETS MASS, VOLUME AND OPERATIONAL CONSTRAINTS
- SYNERGISTIC WITH MARS MISSION

USER COORDINATION:

- CODE RZ: OAET/SPACE EXPLORATION: PSS/JSC
- CODE M: OFFICE OF SPACE FLIGHT (OSF)
- CODE S: OFFICE OF SPACE SCIENCE AND APPLICATION (OSSA)

OVERALL TECHNICAL AND PROGRAMMATIC STATUS:

- CRITICAL SYSTEM ELEMENTS IDENTIFIED
- PEM FUEL CELL LIFE (>1000 HOURS)
- RETRENCH TO BASE R&T IN FY92
- SYNERGISTIC PROGRAMS ADVANCING TECHNOLOGY OUTSIDE AGENCY

MAJOR TECHNICAL/PROGRAMMATIC ISSUES:

- REQUIREMENTS EVOLVING
- NUCLEAR (REACTOR/DIPS) AVAILABILITY

ITP JMB91-002.16

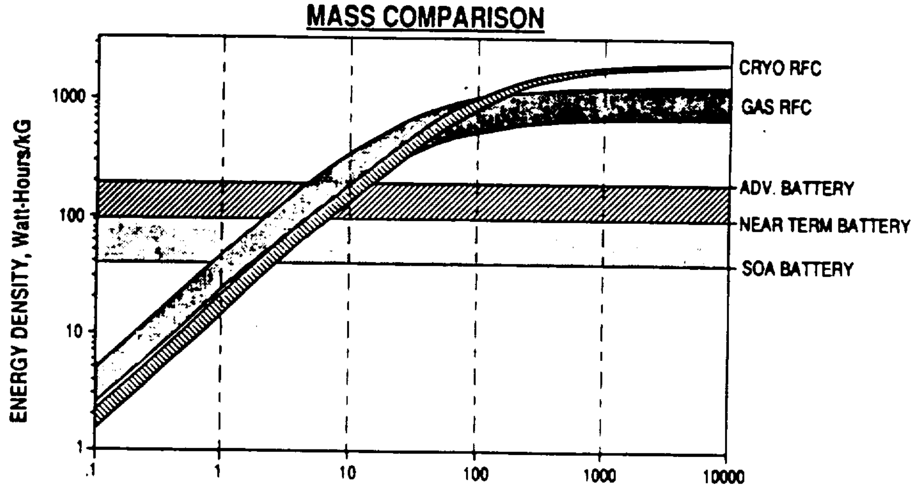
TECHNOLOGY BACK-UP

ITP.JMB91-002.19

SURFACE POWER AND THERMAL MANAGEMENT

REGENERATIVE FUEL CELL vs BATTERIES

MASS COMPARISON

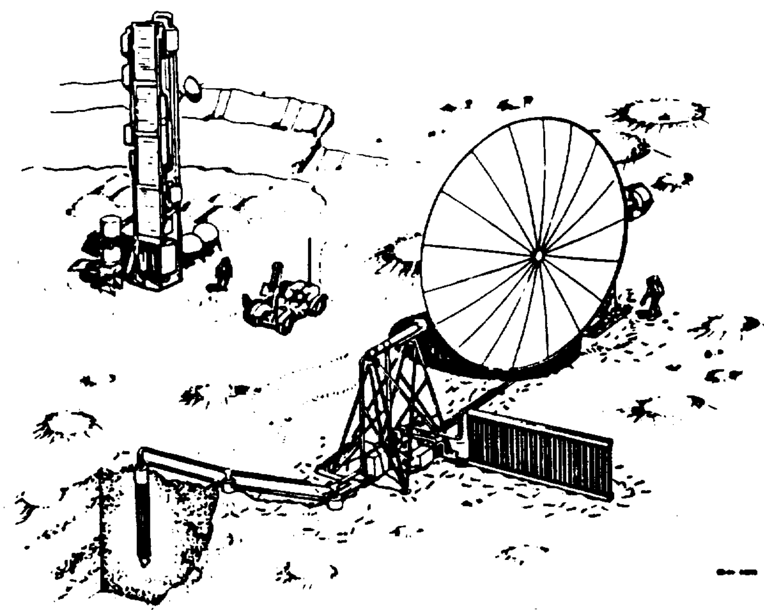


DISCHARGE = CHARGE TIME	TECHNOLOGY OF CHOICE *
< 1 HOUR	BATTERIES
> 1 HOUR but < 10 HOURS	BATTERIES or GAS RFC
> 10 HOURS but <100 HOURS	GAS RFC or CRYO RFC
> 100 HOURS	CRYO RFC

* CHOICE BASED ON MASS OF ENERGY STORAGE SYSTEM ONLY

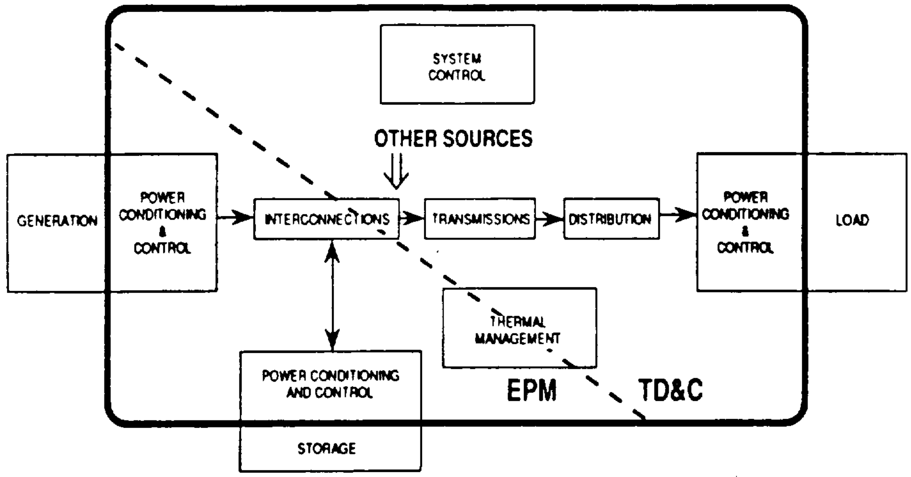
ITP.JMB91-002.9

SURFACE POWER AND THERMAL MANAGEMENT



SURFACE POWER AND THERMAL MANAGEMENT

PMAD ELEMENTS
(EPM and TD&C)



EPM : 110 kg/kW ⟶ 55 kg/kW

TD&C : MISSION DEPENDENT

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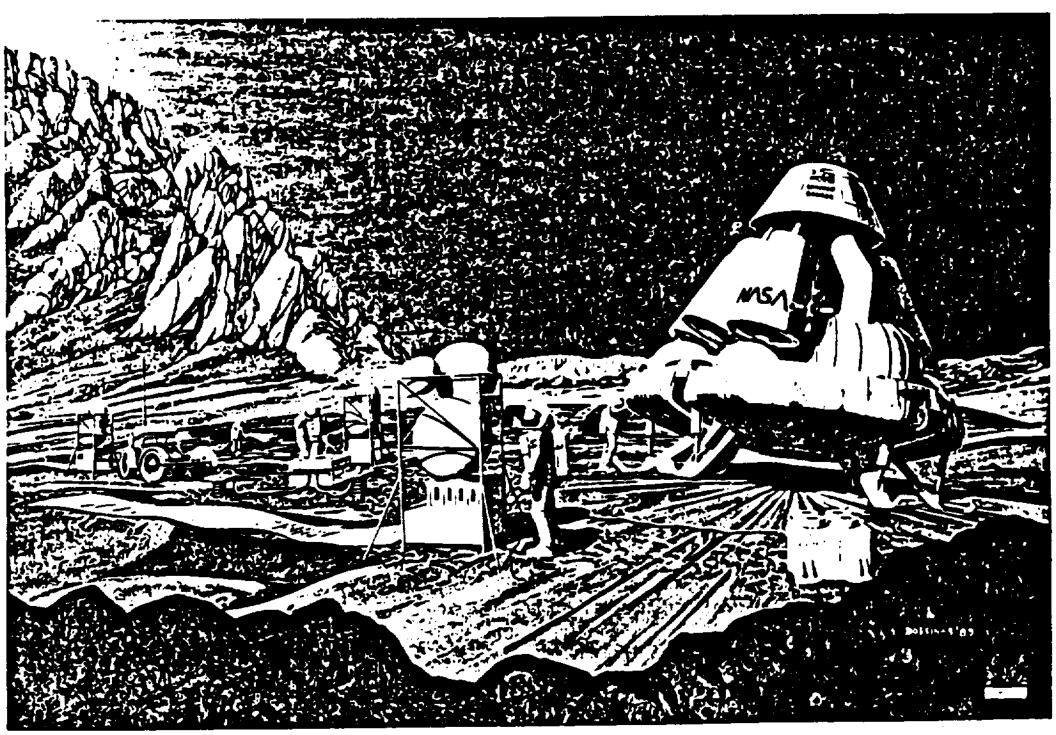

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SPACE PLATFORMS TECHNOLOGY PROGRAM

EARTH ORBITING PLATFORMS
(INCLUDES SPACE STATIONS)

OAET — POWER AND THERMAL MANAGEMENT

SPACE PLATFORMS FOCUSED TECHNOLOGY PROGRAM POWER AND THERMAL MANAGEMENT

PRESENTATION TO:

THE ITP EXTERNAL EXPERT REVIEW TEAM

RONALD C. CULL

JUNE 27, 1991

SPACE PLATFORMS TECHNOLOGY PROGRAM

EARTH ORBITING PLATFORMS
(INCLUDES SPACE STATIONS)

OAET — POWER AND THERMAL MANAGEMENT

AGENDA

- THE PROBLEM
- HOW ADDRESSED
- MARKET SURVEY
- WHAT'S NEEDED
- WHAT IMPACT
- HOW DO WE GET THERE

RC-ITP91 01-13a pm

SPACE PLATFORMS TECHNOLOGY PROGRAM

EARTH ORBITING PLATFORMS
(INCLUDES SPACE STATIONS)

OAET — POWER AND THERMAL MANAGEMENT

THE PROBLEM

- **ENERGY IS CRUCIAL FOR ALL ACTIVITIES IN SPACE**
  - ELECTRICAL POWER
  - THERMAL MANAGEMENT
- **EXTREMELY COSTLY**
  - \$600 - 800/kW hr.
- **NEW MISSIONS REQUIRE CONSIDERABLY MORE**
  - SSF
  - EOS
  - ADTRSS

RC ITP91 01-16 pm

SPACE PLATFORMS TECHNOLOGY PROGRAM

EARTH ORBITING PLATFORMS
(INCLUDES SPACE STATIONS)

OAET — POWER AND THERMAL MANAGEMENT

POSSIBLE SOLUTIONS

- **CUT BACK MISSION RETURNS**
  - TIME AVAILABLE
  - QUANTITY
  - QUALITY
  - LIFETIME
- **MAKE USER MORE EFFICIENT**
  - HIGHER EFFICIENCY LOADS
  - LOAD SCHEDULING AND MANAGEMENT
- **IMPROVE TECHNOLOGY**
  - MASS
  - EFFICIENCY
  - COST

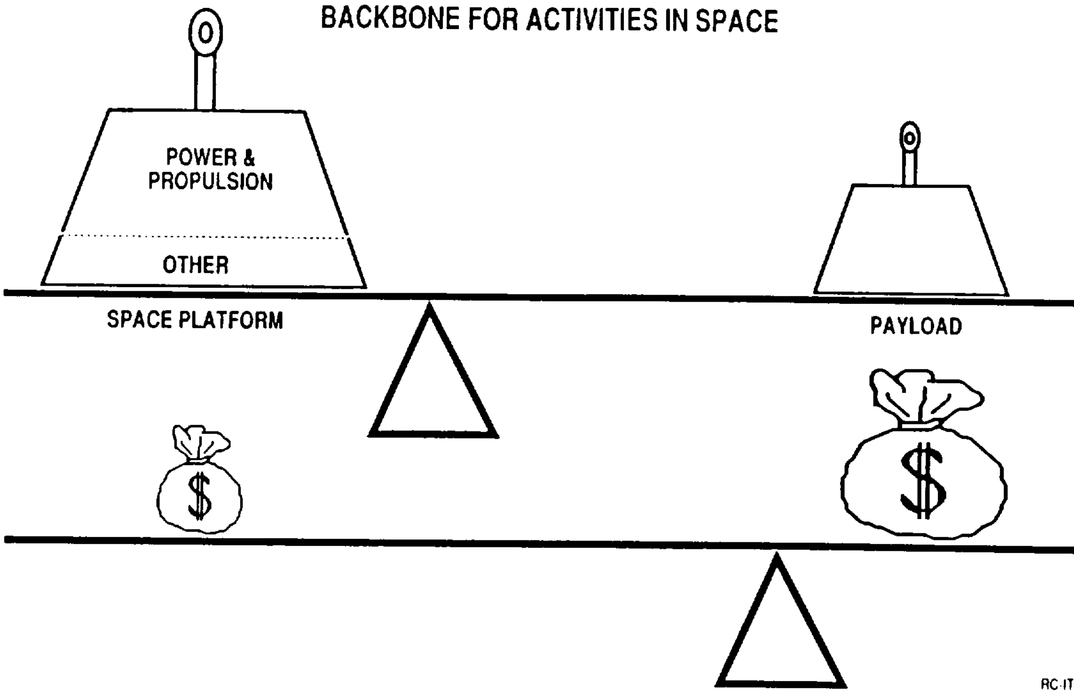
RC ITP91 01-17 pm

SPACE PLATFORMS TECHNOLOGY PROGRAM

EARTH ORBITING PLATFORMS
(INCLUDES SPACE STATIONS)

OAET — POWER AND THERMAL MANAGEMENT

SPACE PLATFORM
BACKBONE FOR ACTIVITIES IN SPACE



RC-ITP91 01-8 pm

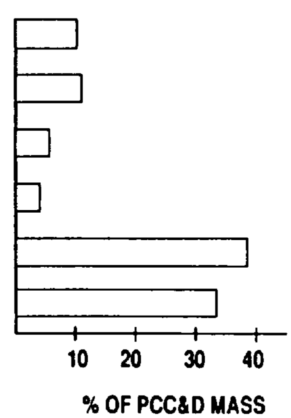
SPACE PLATFORMS TECHNOLOGY PROGRAM

EARTH ORBITING PLATFORMS
(INCLUDES SPACE STATIONS)

OAET — POWER AND THERMAL MANAGEMENT

LOAD MANAGEMENT IMPACT
(SSF EXAMPLE)

CAPACITY (kW)		ELEMENT	MASS (kg)
8 X 9.375	75	GENERATION PC&C	1740
8 X 12.5	100	STORAGE PC&C	1950
8 X 12.5	100	INTERCONNECT	740
8 X 12.5	100	PRIMARY DISTRIBUTION	583
32 X 12.5	400	SECONDARY • •	6177
	< 2000	LOADS PC&C	5500



RCC-91Q01 1

SPACE PLATFORMS TECHNOLOGY PROGRAM

EARTH ORBITING PLATFORMS
(INCLUDES SPACE STATIONS)

OAET — POWER AND THERMAL MANAGEMENT

PHILOSOPHY

- **SCOPE OF NEAR EARTH SPACE ACTIVITIES DETERMINED BY FEDERAL BUDGET REALITIES**
- **TECHNOLOGY CAN BROADEN SCOPE WITHIN CONSTANT BUDGET**
  - NUMBER OF MISSIONS
  - LIFE OF MISSIONS
  - QUALITY OF MISSIONS
- **PLATFORM TECHNOLOGY THRUSTS SHOULD FOCUS ON BROADENING SCOPE**
  - TOWARD LONG LIFE
  - TOWARD IMPROVED PERFORMANCE
  - TOWARD LOW COST

RC-ITP91 01-3 pm

SPACE PLATFORMS TECHNOLOGY PROGRAM

EARTH ORBITING PLATFORMS
(INCLUDES SPACE STATIONS)

OAET — POWER AND THERMAL MANAGEMENT

PHILOSOPHY
(CONT.)

- **MANY TECHNOLOGIES CURRENTLY UNDER DEVELOPMENT**
  - LEVEL OF EFFORT INADEQUATE FOR TIMELY DEVELOPMENT
  - UNFOCUSED
- **SPACE PLATFORM TECHNOLOGY PROGRAM SHOULD FOCUS ON THOSE TECHNOLOGIES THAT:**
  - MAKE SIGNIFICANT IMPACT
  - BROADLY APPLICABLE
  - CAN BE READY IN TIME

RC-ITP91 01-4 pm

SPACE PLATFORMS TECHNOLOGY PROGRAM

EARTH ORBITING PLATFORMS
(INCLUDES SPACE STATIONS)

OAET — POWER AND THERMAL MANAGEMENT

PROGRAM FORMULATION

- IDENTIFY MARKET (USERS)
- DEFINE POWER AND THERMAL REQUIREMENTS
  - MISSION DOMAINS
  - MISSION UNIQUE
- ASSESS TECHNOLOGY IMPACT
- IDENTIFY CRITICAL TECHNOLOGY
- OUTLINE TECHNOLOGY DEVELOPMENT PLANS
  - INTEGRATED OBJECTIVES
  - ROADMAPS
  - FUNDING REQUIREMENTS
  - MILESTONES & DELIVERABLES

RC-ITP91 01 5 pm

SPACE PLATFORMS TECHNOLOGY PROGRAM

EARTH ORBITING PLATFORMS
(INCLUDES SPACE STATIONS)

OAET — POWER AND THERMAL MANAGEMENT

MARKET

- APPLICATIONS
  - EARTH OBSERVING (EOS)
  - ADVANCED COMMUNICATIONS (ATDRSS)
  - ADVANCED SPACE STATIONS (SSF)
- MISSIONS
  - MANNED/UNMANNED
  - CIVIL/COMMERCIAL
- ORBIT REQUIREMENTS
  - LEO → GEO
  - EQUATIONAL → POLAR
- POWER LEVELS
  - 10's W → 10's kW

RC-ITP91 01-40 pm

SPACE PLATFORMS TECHNOLOGY PROGRAM

EARTH ORBITING PLATFORMS

(INCLUDES SPACE STATIONS)

OAET — POWER AND THERMAL MANAGEMENT

SYSTEM REQUIREMENTS

- NEED TO SIGNIFICANTLY IMPROVE NEW SYSTEM DRIVERS
  - LIFE
  - RELIABILITY
  - MAINTAINABILITY
  - ADAPTABILITY
- WHILE MAINTAINING/IMPROVING TRADITIONAL DRIVERS
  - MASS
  - EFFICIENCY
  - COST
- BY IMPROVING TECHNOLOGY
- BY ADDING ATTRIBUTES
  - RECONFIGURABLE
  - SERVICEABLE
  - FAULT TOLERANT
  - AUTONOMOUS

RC-ITP91 01-6 pm

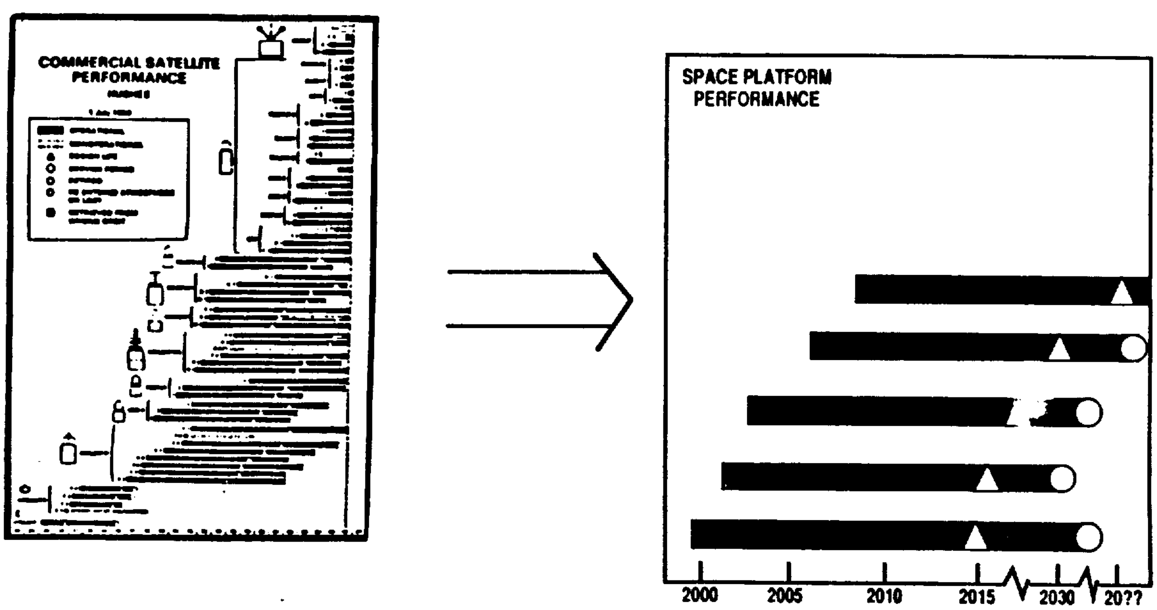
SPACE PLATFORMS TECHNOLOGY PROGRAM

EARTH ORBITING PLATFORMS

(INCLUDES SPACE STATIONS)

OAET — POWER AND THERMAL MANAGEMENT

NEW REGIME



5 - 7 YRS

15 - ? YRS

RC-ITP91 01-7 pm

SPACE PLATFORMS TECHNOLOGY PROGRAM

EARTH ORBITING PLATFORMS

(INCLUDES SPACE STATIONS)

OAET — POWER AND THERMAL MANAGEMENT

DEDICATED vs UTILITY POWER SYSTEMS

REQUIREMENTS

CHARACTERISTIC	DEDICATED	UTILITY
Source Capacity	1 -10 kW	kW - MW
Source Number	1 -2	Multiple
Growth	No	Yes
Lifetime	Fixed	Extendible
Repairable	No	Yes
Load/Source Cap.	~ 1	>>1
Physical Size	Small	Large
Flexibility	Loads fixed	Loads vary
Manned	No	Yes

APPROACH

DEDICATED

FOCUS ON MEETING
- MISSION SPECIFIC REQUIREMENTS
- ADAPT EXISTING SPACECRAFT BUS

UTILITY

- FOCUS ON MAJOR SYSTEM ELEMENTS
  - GENERAL REQUIREMENTS
  - FUNCTIONS
  - MUTUAL COMPATIBILITY
- COMBINE MODULAR ELEMENTS
- INCLUDE REQUIREMENTS FOR
  - REPAIRS
  - USER TRANSPARENCY
  - EVOLUTIONARY DEVELOPMENT

UTILITY APPROACH INCREASES DDT&E COSTS BUT BROADENS APPLICABILITY AND LOWERS LIFE CYCLE COSTS.

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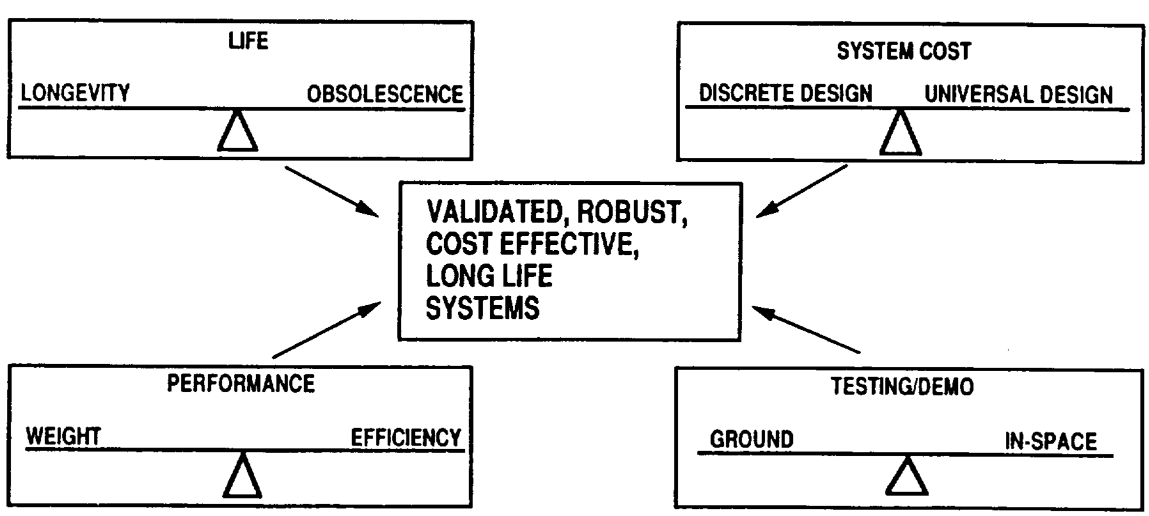
SPACE PLATFORMS TECHNOLOGY PROGRAM

EARTH ORBITING PLATFORMS

(INCLUDES SPACE STATIONS)

OAET — POWER AND THERMAL MANAGEMENT

TECHNOLOGY ASSESSMENT



RC-ITP91 01-14 pm

SPACE PLATFORMS TECHNOLOGY PROGRAM

EARTH ORBITING PLATFORMS

(INCLUDES SPACE STATIONS)

OAET — POWER AND THERMAL MANAGEMENT

PLAN

- FOCUS ON MISSIONS
- USE BASE PROGRAM TECHNOLOGY
- ENHANCE TECHNOLOGY DEVELOPMENT
  - TIMELINESS
  - DEVELOPMENT LEVEL
- DEMONSTRATE AT SYSTEMS LEVEL
- MOVE INTO FLIGHT PROGRAM

RC-ITP91 01-19 pm

SPACE PLATFORMS TECHNOLOGY PROGRAM

EARTH ORBITING PLATFORMS

(INCLUDES SPACE STATIONS)

OAET — POWER AND THERMAL MANAGEMENT

SPACE RESEARCH AND TECHNOLOGY GOAL

TO ENSURE THE EFFECTIVE TRANSFER OF TECHNOLOGY TO MISSION APPLICATIONS BY CONDUCTING FOCUSED TECHNOLOGY PROGRAMS, WITH NEGOTIATED AND COORDINATED USER HAND-OFF AGREEMENTS WITH THE OTHER PROGRAM OFFICES IN NASA.

RC-ITP91 01-11 pm

SPACE PLATFORMS TECHNOLOGY PROGRAM

EARTH ORBITING PLATFORMS

(INCLUDES SPACE STATIONS)

OAET — POWER AND THERMAL MANAGEMENT

OBJECTIVES

- **Programmatic**

  Develop and demonstrate integrated power and thermal management technologies for near earth missions.

- **Technical**
  - Reduce array area by 30% with 3X increased rad. tolerance
  - 3X increase in battery energy density
  - 2X reduction in PMAD system mass
  - 2X reduction in radiator mass and area
  - Extend lifetimes to 15-30 years

SCHEDULE

1996 - Demonstrate 300 W/kg planar PV, 100 W/kg InP concentrator module
1996 - Ground test cryogenic capillary pumped loop
1997 - Demonstrate advanced PMAD integrated avionics system
1997 - Ground demo, integrated 2 kW solar dynamic system
1998 - Demonstrate 1-2 kg/m^2 thermal management system
1998 - Complete advanced EPSAT
1999 - Demonstrate flight weight 100 Wh/kg battery
2000 - Demonstrate durable high temp. electronics subsystem (200-600 $^{\circ}$C)

RESOURCES*

RESOURCES*	CURRENT	STRATEGIC
• 1991	---	---
• 1992	---	---
• 1993	---	$ 5.1 M
• 1994	---	$ 10.2 M
• 1995	---	$ 13.5 M
• 1996	---	$ 14.3 M
• 1997	---	$ 14.7 M

*Includes both Earth Orbiting Platforms and Space Stations

PARTICIPANTS

- **Goddard**

  Responsibility includes cryogenic bus technology and low temperature thermal management subsystems

- **JPL**

  Responsibility includes lightweight planar PV and lithium battery technology and integrated PICs

- **LeRC**

  Responsibility includes concentrator PV, InP cells, lightweight Ni/H2 and Na/S, batteries moderate and high temperature radiators, integrated autonomous PMAD and high temperature electronics, solar dynamic system

RC-ITP91 01-1 pm

SPACE PLATFORMS TECHNOLOGY PROGRAM

EARTH ORBITING PLATFORMS

(INCLUDES SPACE STATIONS)

OAET — POWER AND THERMAL MANAGEMENT

OBJECTIVE

PROVIDE THE TECHNOLOGY TO MEET POWER SYSTEM REQUIREMENTS FOR FUTURE NEAR EARTH SPACE MISSIONS, INCLUDING GROWTH SPACE STATIONS AND EARTH ORBITING SPACECRAFT.

TECHNOLOGY AREAS:

- PHOTOVOLTAIC ENERGY CONVERSION (CELLS/ARRAYS)
- THERMAL ENERGY CONVERSION (SOLAR DYNAMIC)
- CHEMICAL ENERGY STORAGE (BATTERIES)
- POWER MANAGEMENT AND DISTRIBUTION
- THERMAL MANAGEMENT AND DISTRIBUTION

RC-ITP91 01-12 pm

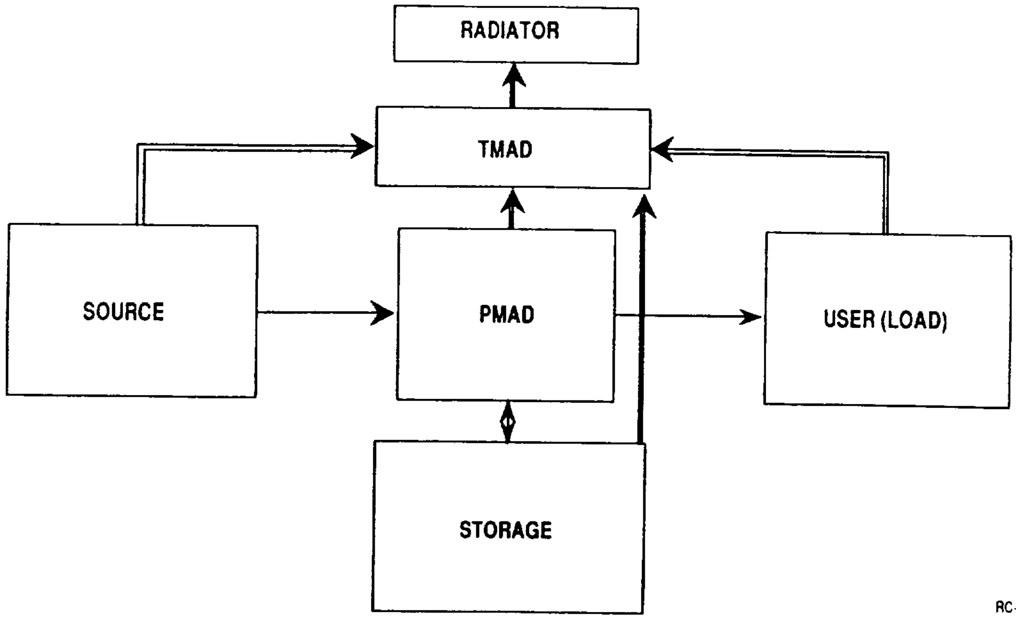
SPACE PLATFORMS TECHNOLOGY PROGRAM

EARTH ORBITING PLATFORMS

(INCLUDES SPACE STATIONS)

OAET — POWER AND THERMAL MANAGEMENT

POWER AND THERMAL SUBSYSTEMS
(ENERGY FLOW)



RC-ITP91 01-13 pm

SPACE PLATFORMS TECHNOLOGY PROGRAM

EARTH ORBITING PLATFORMS

(INCLUDES SPACE STATIONS)

OAET — POWER AND THERMAL MANAGEMENT

APPLICATIONS INVESTIGATED

EOS

TDRSS

SSF

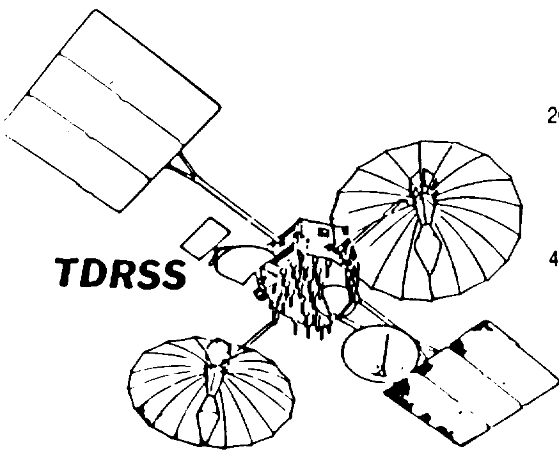
RC-ITP91 01-9 pm

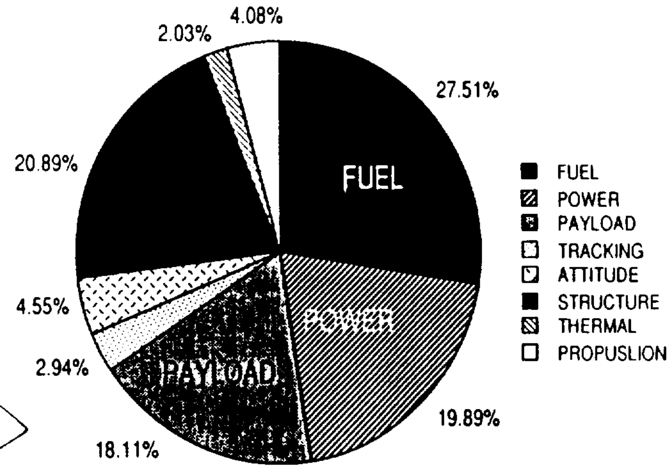
SPACE PLATFORMS TECHNOLOGY PROGRAM

EARTH ORBITING PLATFORMS
(INCLUDES SPACE STATIONS)

OAET — POWER AND THERMAL MANAGEMENT

TRACKING AND DATA RELAY SATELLITE SYSTEM WET MASS





TOTAL MASS = 2123 kg

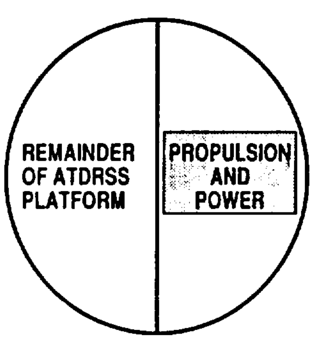
SPACE PLATFORMS TECHNOLOGY PROGRAM

EARTH ORBITING PLATFORMS
(INCLUDES SPACE STATIONS)

OAET — POWER AND THERMAL MANAGEMENT

PROPULSION AND POWER DRIVERS ON ATDRSS

IMPROVEMENTS IN PROPULSION AND POWER CAN SIGNIFICANTLY IMPROVE ATDRSS



PROPULSION AND POWER COMPRISE ABOUT ONE-HALF OF THE TOTAL MASS OF ATDRSS

A 2X IMPROVEMENT IN PROPULSION AND POWER WOULD DOUBLE THE PAYLOAD ON ATDRSS

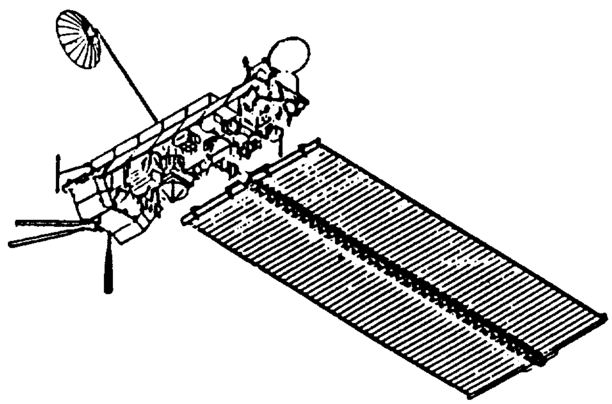
RC-ITP91 01-33 pm

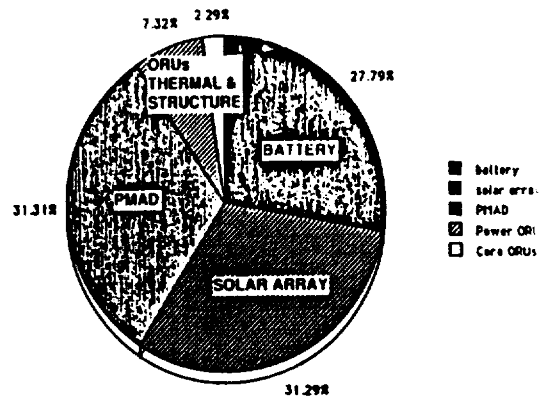
SPACE PLATFORMS TECHNOLOGY PROGRAM

EARTH ORBITING PLATFORMS
(INCLUDES SPACE STATIONS)

OAET — POWER AND THERMAL MANAGEMENT

ELECTRICAL POWER SYSTEM WEIGHTS





TOTAL EPS WEIGHT IS 3264.8 lbs (1484 kg)

SPACE PLATFORMS TECHNOLOGY PROGRAM

EARTH ORBITING PLATFORMS
(INCLUDES SPACE STATIONS)

OAET — POWER AND THERMAL MANAGEMENT

PHOTOVOLTAIC ENERGY CONVERSION

OBJECTIVE

PROVIDE THE TECHNOLOGY FOR PHOTOVOLTAIC ARRAYS WITH IMPROVED CONVERSION EFFICIENCY, REDUCED MASS, REDUCED COST, AND INCREASED OPERATING LIFE FOR ADVANCED SPACE MISSIONS

SPECIFIC LONG-RANGE GOALS ARE TO DEVELOP THE TECHNOLOGY BASE FOR PHOTOVOLTAIC ARRAYS WITH SPECIFIC POWER OF 300 W/kg WITH SUBSTANTIAL REDUCTIONS IN SIZE, COST, AND INCREASES IN END-OF-LIFE POWER CAPABILITY

TECHNOLOGY AREAS

- ADVANCED PHOTOVOLTAIC CELL TECHNOLOGY
- HIGH-PERFORMANCE ARRAYS
- HIGH-POWER ARRAYS

RC-ITP91 01-20 pm

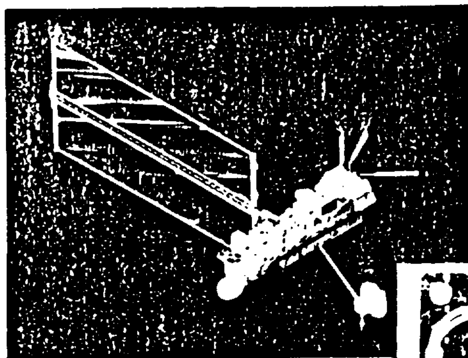
SPACE PLATFORMS TECHNOLOGY PROGRAM

EARTH ORBITING PLATFORMS
(INCLUDES SPACE STATIONS)

OAET — POWER AND THERMAL MANAGEMENT

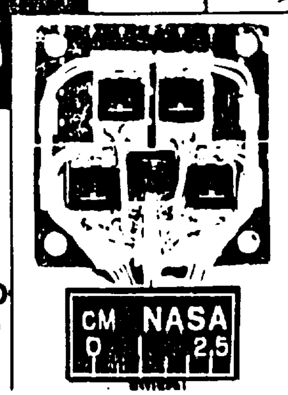
EOS POWER TECHNOLOGY

EOS (SAFE BASELINE)
29 W/Kg



APSA (Si)
77 W/Kg

ADVANCED APSA (InP)
99 W/Kg



PV CONCEPTS FOR EOS PLATFORMS

SPACE PLATFORMS TECHNOLOGY PROGRAM

EARTH ORBITING PLATFORMS
(INCLUDES SPACE STATIONS)

OAET — POWER AND THERMAL MANAGEMENT

OBJECTIVE

TO DEVELOP AN ULTRA-LIGHT-WEIGHT, HIGH PERFORMANCE, ADVANCED DEPLOYABLE PHOTOVOLTAIC ARRAY DESIGN THAT WILL BE SUITABLE FOR A BROAD RANGE OF LONG-TERM NASA AND U.S. COMMERCIAL SPACE APPLICATIONS FOR THE PERIOD BEYOND 1990

NEAR-TERM SPECIFIC POWER: 130 W/kg*
LONG-TERM SPECIFIC POWER: 300 W/kg*

*BOL ARRAY POWER FOR GEO

RC-ITP91 01-45 pm

SPACE PLATFORMS TECHNOLOGY PROGRAM

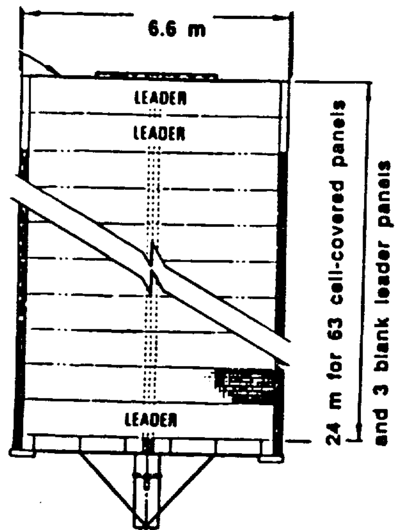
EARTH ORBITING PLATFORMS

(INCLUDES SPACE STATIONS)

OAET — POWER AND THERMAL MANAGEMENT

APSA ARRAY FOR EOS

- Thin silicon cells, 13.5% eff
- Retractable
- Carbon-loaded Kapton blanket
- Graphite/epoxy structure
- Fiberglass boom
- Aluminum canister



P_{EOL} = 13,136 W
(5 year/705 km/98 deg incl.)

Peformance

Without Solar Array Drive Assembly (SADA)

Specific Power = 96 W/kg
Power Density = 94 W/m2 > 10% cont.

Specific Power = 88 W/kg
Power Density = 94 W/m2 > 20% cont.

With SADA/Boom (27 kg allocation)

Specific Power = 84 W/kg
Power Density = 94 W/m2 > 10% cont.

Specific Power = 77 W/kg
Power Density = 94 W/m2 > 20% cont.

AREA ABOUT 82% OF EOS ARRAY AREA

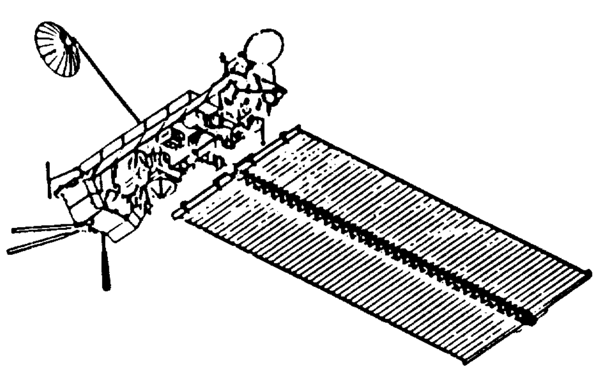
SPACE PLATFORMS TECHNOLOGY PROGRAM

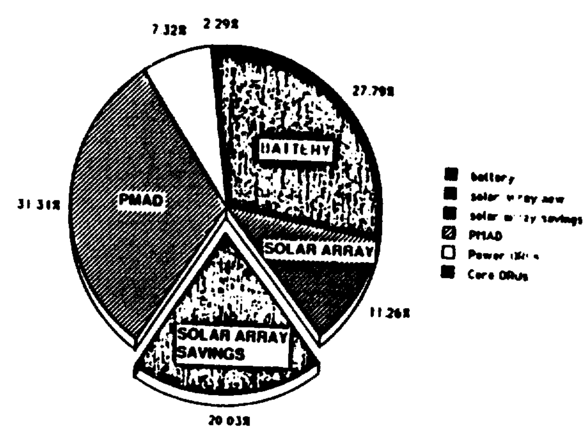
EARTH ORBITING PLATFORMS

(INCLUDES SPACE STATIONS)

OAET — POWER AND THERMAL MANAGEMENT

ELECTRIC POWER SYSTEM WEIGHTS





ADVANCED PHOTOVOLTAIC SOLAR ARRAY (APSA) SAVES 297.3 kg (654 lb)

SPACE PLATFORMS TECHNOLOGY PROGRAM

EARTH ORBITING PLATFORMS
(INCLUDES SPACE STATIONS)

OAET — POWER AND THERMAL MANAGEMENT

ADVANCED PHOTOVOLTAIC SOLAR ARRAY

- GOAL: 10X IMPROVEMENT IN PHOTOVOLTAIC ARRAY DESIGN
  - ACHIEVED NEAR-TERM GOAL OF 130 W/kg
  - WORKING TOWARD LONG-TERM GOAL OF 300 W/kg
- LABORATORY VERIFICATION WITH PROTOTYPE BLANKET ASSEMBLY AND LIGHT-WEIGHT MAST SYSTEM
  - 2X IMPROVEMENT OVER SAFE ARRAY AND 3X-4X IMPROVEMENT OVER CURRENT RIGID-PANEL ARRAYS
- PLAN TO COMPLETE PROTOTYPE COMPONENTS AND CONDUCT FUNCTIONAL TESTS

ACTIVE INVOLVEMENT OF USERS WILL ENSURE TIMELY COMPLETION TO MEET LAUNCH DATES

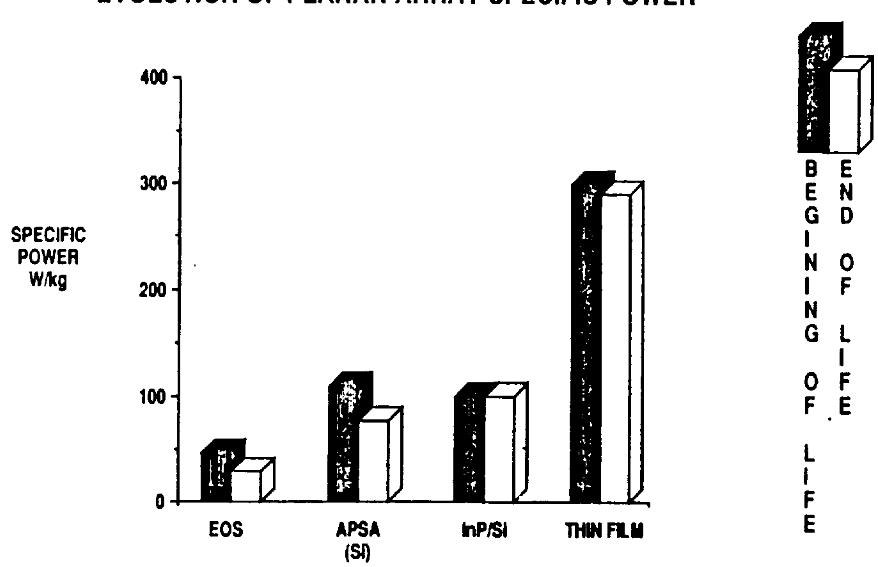
RC-ITP91 01-84 pm

SPACE PLATFORMS TECHNOLOGY PROGRAM

EARTH ORBITING PLATFORMS
(INCLUDES SPACE STATIONS)

OAET — POWER AND THERMAL MANAGEMENT

EVOLUTION OF PLANAR ARRAY SPECIFIC POWER



RC-ITP91 01-22 pm

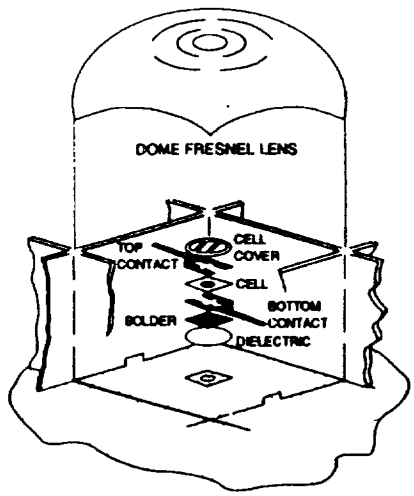
SPACE PLATFORMS TECHNOLOGY PROGRAM

EARTH ORBITING PLATFORMS
(INCLUDES SPACE STATIONS)

OAET — POWER AND THERMAL MANAGEMENT

CONCENTRATOR TECHNOLOGY

LeRC MINI-DOME FRESNEL LENS CONCENTRATOR ELEMENT — POWER TECHNOLOGY DIVISION



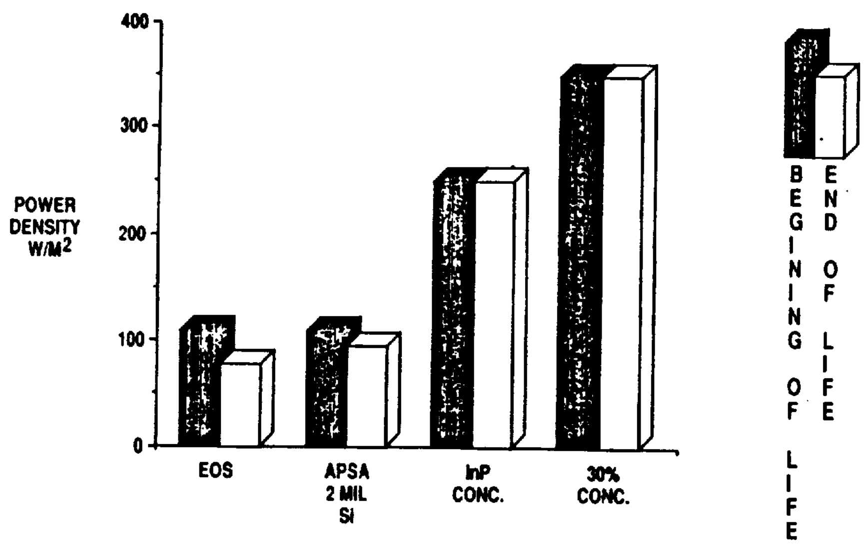
RC-ITP91 01-46 pm

SPACE PLATFORMS TECHNOLOGY PROGRAM

EARTH ORBITING PLATFORMS
(INCLUDES SPACE STATIONS)

OAET — POWER AND THERMAL MANAGEMENT

EVOLUTION OF ARRAY POWER DENSITY



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SPACE PLATFORMS TECHNOLOGY PROGRAM

EARTH ORBITING PLATFORMS

(INCLUDES SPACE STATIONS)

OAET — POWER AND THERMAL MANAGEMENT

Project Overview and Resources

Technology Program: Space Platforms — WBS No.: 694-11-05

Technology Area: Earth Orbiting Platforms

Technology Element: Power

Technology Sub-Element: Power Generation (Photovoltaic)

Milestones:

1996 300 w/kg planar blanket fabricated

1996 100 w/kg InP concentrator panel demo

1998 Demo thin film cell array > 300 w/kg

1998 Demo 50 w InP concentrator module through environmental testing

	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000
R&D Resources:	0	0	0.6	1.3	1.9	2.3	2.5	3.3	0	0
C of F ($M):	0	0	0	0	0	0	0	0	0	0

SPACE PLATFORMS TECHNOLOGY PROGRAM

EARTH ORBITING PLATFORMS

(INCLUDES SPACE STATIONS)

OAET — POWER AND THERMAL MANAGEMENT

CHEMICAL ENERGY CONVERSION

OBJECTIVES

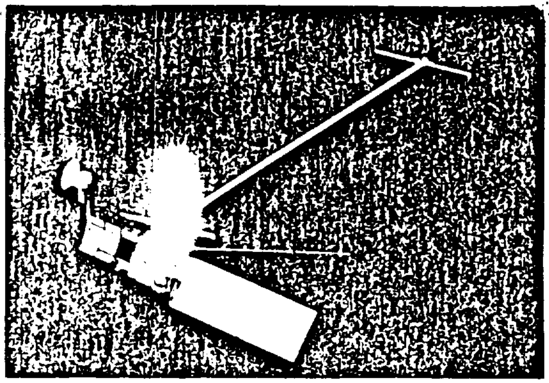
PROVIDE THE TECHNOLOGY BASE FOR ADVANCED ELECTROCHEMICAL ENERGY CONVERSION AND STORAGE SYSTEMS REQUIRED TO SUPPORT THE LOW TO HIGH POWER NEEDS OF FUTURE MANNED AND UNMANNED SPACE APPLICATIONS, THE CYCLE LIFE REQUIREMENTS OF LOW-EARTH-ORBIT (LEO) SYSTEMS

TECHNOLOGY AREAS

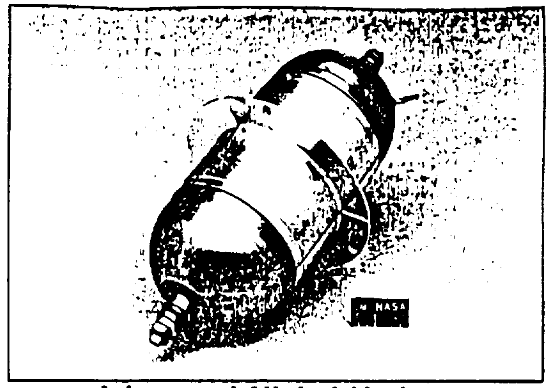
- SECONDARY BATTERIES
- ADVANCED ELECTROCHEMICAL ENERGY STORAGE

RC-ITP91 01-48 pm

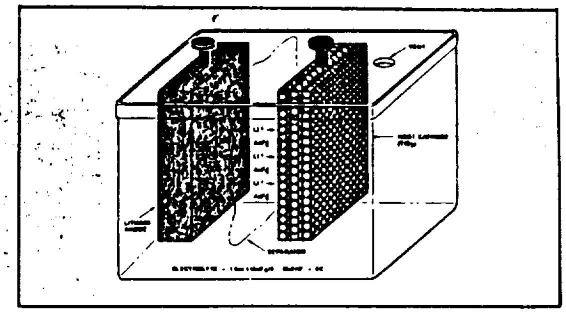
PROGRESS IN ENERGY STORAGE



EOS Nickel-Hydrogen
(10 W-hr/Kg)



Advanced Nickel-Hydrogen
(24 W-hr/Kg)



Future Applications
Chemical Energy Storage
(>40 W-hr/Kg)

RP89 415

SPACE PLATFORMS TECHNOLOGY PROGRAM

EARTH ORBITING PLATFORMS
(INCLUDES SPACE STATIONS)

OAET — POWER AND THERMAL MANAGEMENT

LIGHT-WEIGHT NiH_2 CELLS NEAR-TERM ADVANCEMENT OF PROVEN TECHNOLOGY

OBJECTIVES

- IMPROVED SPECIFIC ENERGY CELLS
- IMPROVED SPECIFIC VOLUME CELLS

APPROACH

- COMPUTER-AIDED DESIGN OPTIMIZATION
- TECHNOLOGY DEVELOPMENT
  - LIGHT-WEIGHT NICKEL ELECTRODE
  - OPTIMIZATION OF KOH CONCENTRATION
- VERIFICATION TESTING VIA BOILER PLATE AND FLIGHT-WEIGHT CELLS

RC-ITP91.01-25.pm

SPACE PLATFORMS TECHNOLOGY PROGRAM

EARTH ORBITING PLATFORMS
(INCLUDES SPACE STATIONS)

OAET — POWER AND THERMAL MANAGEMENT

LIGHT-WEIGHT NiH_2 CELLS NEAR-TERM ADVANCEMENT OF PROVEN TECHNOLOGY
(Continued)

GOALS

- 2.0 x SOA SPECIFIC ENERGY
- 1.2 x SOA SPECIFIC VOLUME
- ENHANCED LEO AND GEO MISSIONS, SUCH AS:
  - SSF
  - PLATFORMS
  - SPACE TELESCOPE
  - COMMUNICATION SATELLITES

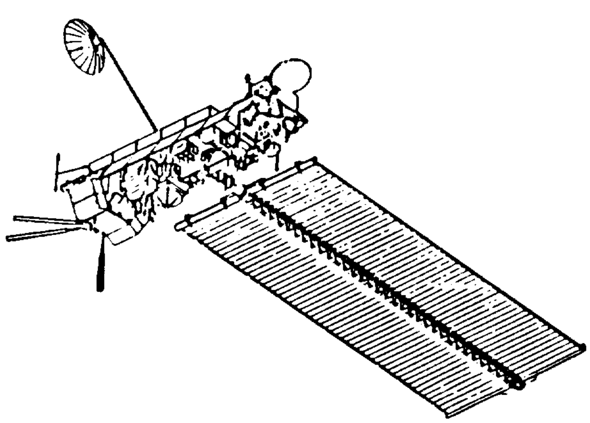
RC-ITP91 01-50 pm

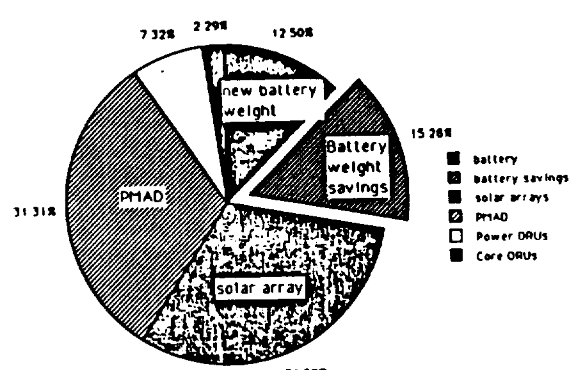
SPACE PLATFORMS TECHNOLOGY PROGRAM

EARTH ORBITING PLATFORMS
(INCLUDES SPACE STATIONS)

OAET — POWER AND THERMAL MANAGEMENT

ELECTRICAL POWER SYSTEM WEIGHTS





ADVANCED BATTERY TECHNOLOGY CAN SAVE ~227 kg (~500 lb)

SPACE PLATFORMS TECHNOLOGY PROGRAM

EARTH ORBITING PLATFORMS

(INCLUDES SPACE STATIONS)

OAET — POWER AND THERMAL MANAGEMENT

Project Overview and Resources

Technology Program:	Space Platforms	WBS No.: 694-11-06
Technology Area:	Earth Orbiting Platforms	
Technology Element:	Power	
Technology Sub-Element:	Energy Storage	

Milestones:

- 1995 Demo 100 Wh/kg boilerplate cells to 1000+ cycles (GEO) (Li and Ni/H2)
- 1997 Define engineering model components for 150 Wh/kg battery
- 1999 Demo 100 Wh/kg flightweight battery
- 2000 Demo 150 Wh/kg (engineering model)

	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000
R&D Resources:	0	0	0.7	1.2	1.6	1.6	1.4	1.4	0	0
C of F ($M):	0	0	0	0	0	0	0	0	0	0

SPACE PLATFORMS TECHNOLOGY PROGRAM

EARTH ORBITING PLATFORMS

(INCLUDES SPACE STATIONS)

OAET — POWER AND THERMAL MANAGEMENT

THERMAL ENERGY CONVERSION

OBJECTIVES

- DEVELOP THE TECHNOLOGY BASE TO PROVIDE ADVANCED HIGH-EFFICIENCY, HIGH-TEMPERATURE (1050 - 1400 K), LONG-LIFE SOLAR DYNAMIC STIRLING/BRAYTON POWER SYSTEM FOR A WIDE RANGE OF NASA AND COMMERCIAL SPACE POWER NEEDS

TECHNOLOGY AREAS

- HIGH-TEMPERATURE SOLAR DYNAMICS

RC-ITP91 01-27.pm

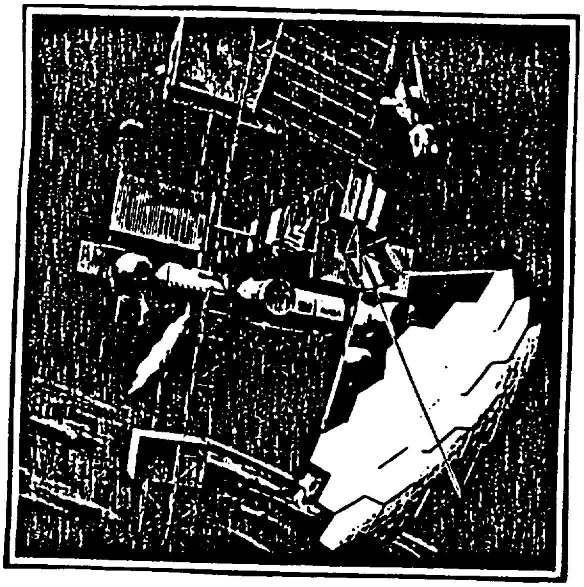
(INCLUDES SPACE STATIONS)

OAET — POWER AND THERMAL MANAGEMENT

THERMAL ENERGY CONVERSION

MISSION & BENEFITS
- EARTH ORBITING PLATFORMS -

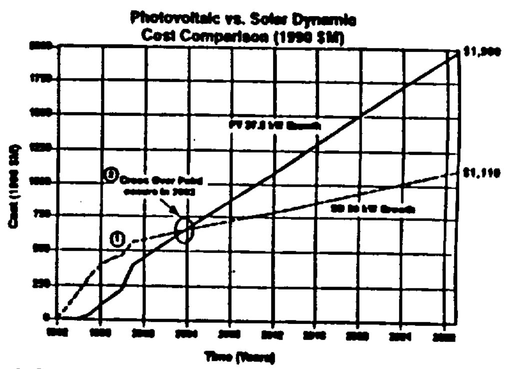
SPACE STATION FREEDOM



QUALITATIVE BENEFITS

- MORE FLEXIBILITY
- LONG LIFE COMPONENTS
- LESS DRAG
- LOWER MASS
- LOWER RECURRING COSTS
- LESS AGGREGATE EVA

QUANTITATIVE BENEFITS



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SPACE PLATFORMS TECHNOLOGY PROGRAM
EARTH ORBITING PLATFORMS
(INCLUDES SPACE STATIONS)

OAET — POWER AND THERMAL MANAGEMENT

TECHNOLOGY ISSUES

SYSTEM LEVEL

- SOLAR DYNAMIC SYSTEM INTERACTIONS
- SCALABILITY
- POWER SHARING (AC & DC) SOURCES

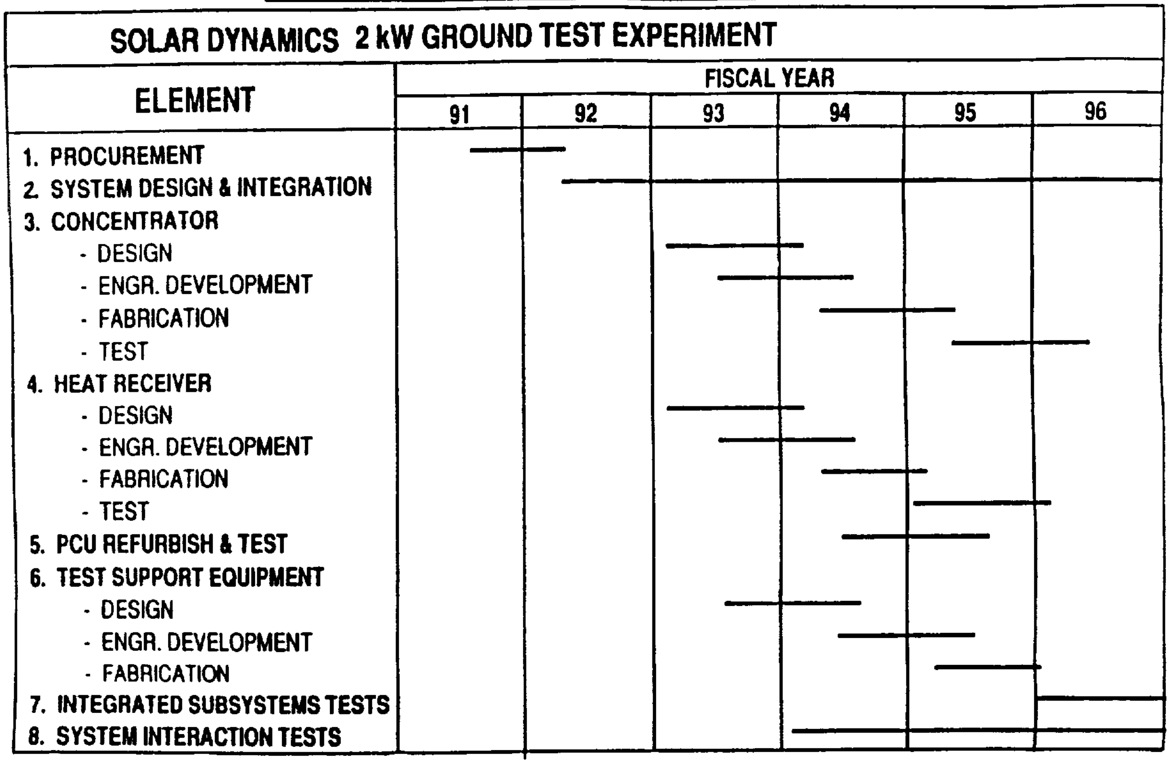
SUBSYSTEM LEVEL

- CONCENTRATOR
  - FABRICATION PROCESSES
  - OPTICS
  - DEPLOYMENT
- PCU
  - START-UP
  - TRANSIENT OPERATION
  - OFF-DESIGN OPERATION
- HEAT RECEIVER
  - HOT SPOTS
  - THERMAL RATCHETING
- RADIATOR
  - NONE
- CONTROLS
  - PARALLEL OPERATION
  - LOAD FOLLOWING

SPACE PLATFORMS TECHNOLOGY PROGRAM

EARTH ORBITING PLATFORMS
(INCLUDES SPACE STATIONS)

OAET — POWER AND THERMAL MANAGEMENT



SPACE PLATFORMS TECHNOLOGY PROGRAM

EARTH ORBITING PLATFORMS
(INCLUDES SPACE STATIONS)

OAET — POWER AND THERMAL MANAGEMENT

Project Overview and Resources

Technology Program:	Space Platforms	WBS No.: 694-11-02
Technology Area:	Earth Orbiting Platforms	
Technology Element:	Power	
Technology Sub-Element:	Power Generation (Solar Dynamic)	

Milestones:

- 1994 Select Brayton or Stirling PCU
- 1995 Demo 30% efficient concentrator cascade cell
- 1997 Demo 300 W/m^2 refractive concentrator PV module (750 W)
- 1997 Ground demo 2 kW advanced solar dynamic system
- 1999 Identify system level SD issues

	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000
R&D Resources:	0	0	1.2	3.5	3.6	3.4	3.0	1.9	0	0
C of F ($M):	0	0	0	0	0	0	0	0	0	0

SPACE PLATFORMS TECHNOLOGY PROGRAM

EARTH ORBITING PLATFORMS

(INCLUDES SPACE STATIONS)

OAET — POWER AND THERMAL MANAGEMENT

POWER MANAGEMENT

OBJECTIVES

- DEVELOP THE ELECTRICAL POWER SYSTEMS CONDITIONING, CONTROL, AND DISTRIBUTION TECHNOLOGY NEEDED FOR EARTH ORBITAL SPACE MISSIONS

TECHNOLOGY AREAS

- HIGH-VOLTAGE, HIGH-POWER SYSTEMS
- HIGH-DENSITY POWER SYSTEMS
- FAULT TOLERANT/POWER INTEGRATED CIRCUITS

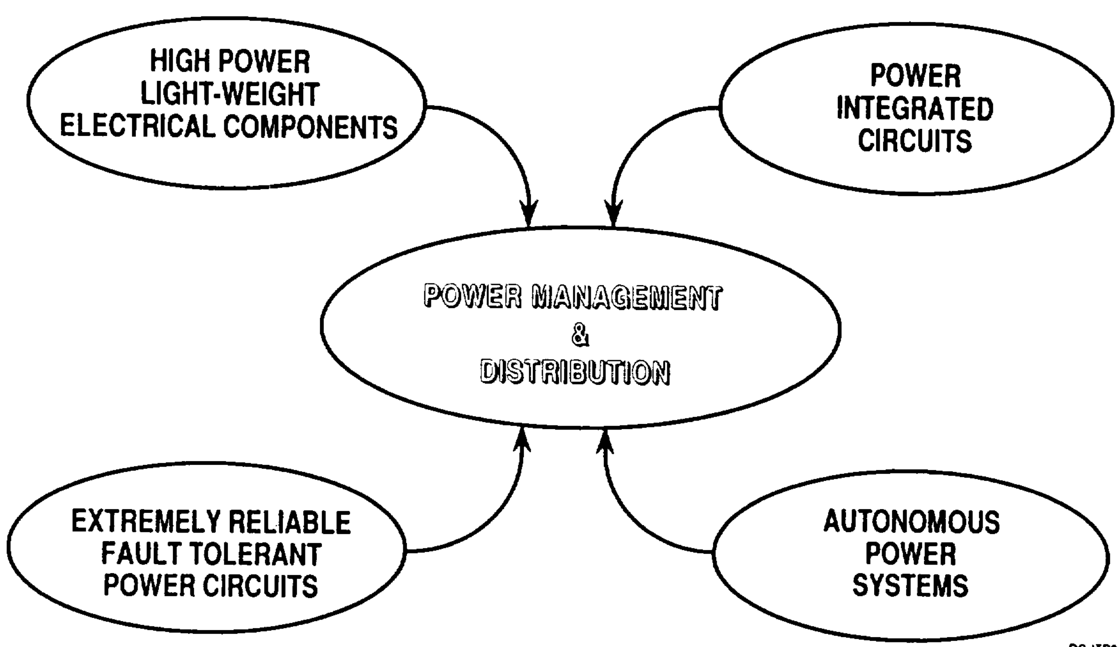
RC-ITP91 01-28 pm

SPACE PLATFORMS TECHNOLOGY PROGRAM

EARTH ORBITING PLATFORMS

(INCLUDES SPACE STATIONS)

OAET — POWER AND THERMAL MANAGEMENT



RC-ITP91 01-29 pm

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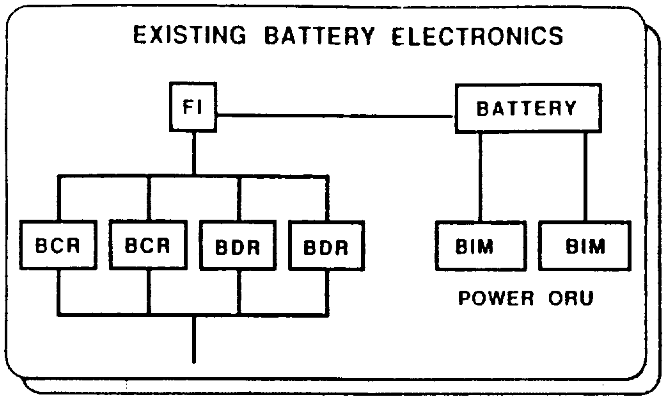
SPACE PLATFORMS TECHNOLOGY PROGRAM

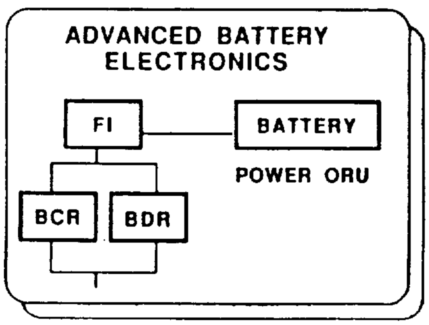
EARTH ORBITING PLATFORMS

(INCLUDES SPACE STATIONS)

OAET — POWER AND THERMAL MANAGEMENT



ASSEMBLY	MASS (LBS.)
2ea BCR	26
2ea BDR	52
2ea BIM	6
TOTAL PER POWER ORU	84



ASSEMBLY	MASS (LBS.)
2ea BDC	34

SIGNIFICANCE

EOS POWER SYSTEM MASS SAVINGS 50lbs PER POWER ORU OR 200lbs PER PLATFORM.

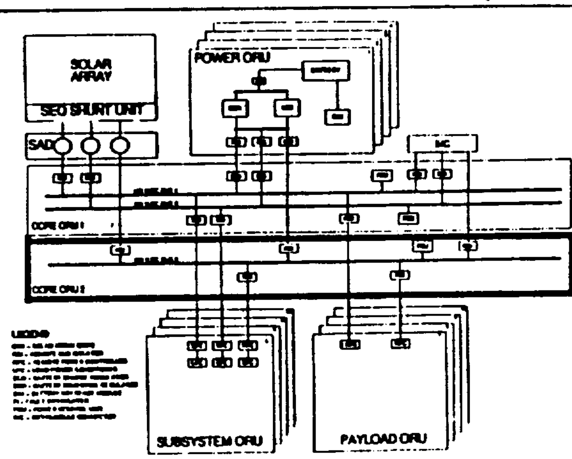
SPACE PLATFORMS TECHNOLOGY PROGRAM

EARTH ORBITING PLATFORMS

(INCLUDES SPACE STATIONS)

OAET — POWER AND THERMAL MANAGEMENT

POWER SUBSYSTEM BLOCK DIAGRAM Eos



FAULT TOLERANCE SAVINGS

REDUCE NUMBER OF POWER BUSES FROM THREE TO TWO

- 2 LPCs 4.4 lbs
- 3 RPCs 2.3 lbs
- 1 PCU 6.5 lbs
- 15 RBIs 30.0 lbs
- ORU HARNESS 16.0 lbs

TOTAL SAVINGS 59.2 lbs (27 kgs)

NOTE; ORU #2 MAY BE ABLE TO BE ELIMINATED ENTIRELY, DEPENDING ON THERMAL CONSIDERATIONS. IF ORU IS ELIMINATED ENTIRELY, THE WEIGHT SAVINGS WOULD BE 210 lbs (95 kgs)

SPACE PLATFORMS TECHNOLOGY PROGRAM

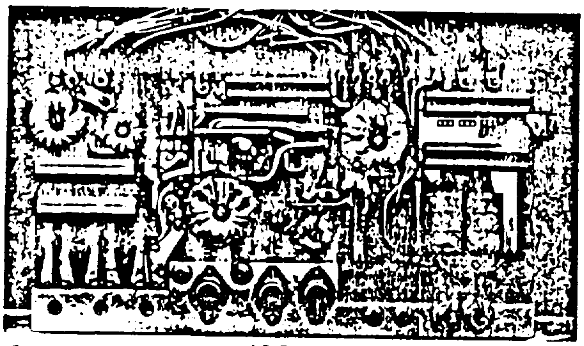
EARTH ORBITING PLATFORMS
(INCLUDES SPACE STATIONS)

OAET — POWER AND THERMAL MANAGEMENT

HIGH DENSITY POWER/POWER INTEGRATED CIRCUITS

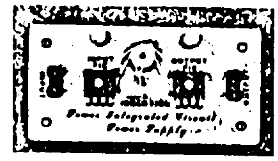
Goal: Achieve high density power technologies of 10 W/in.^{3} by year 2000

STATE OF THE ART
DISCRETES: VOLUME/MASS INTENSIVE



13.5 in.
1 W/in.^{3}

100 W
30 V
dc S/C
POWER SUPPLY



6.5 in.
4 W/in.^{3}

IMPACT: 80% MASS REDUCTION
80% VOLUME REDUCTION
89% PARTS REDUCTION
50% LOSS REDUCTION

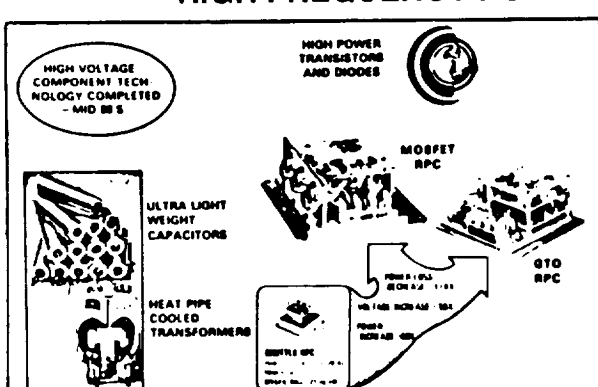
Plan: Hold power system to 20% of total system

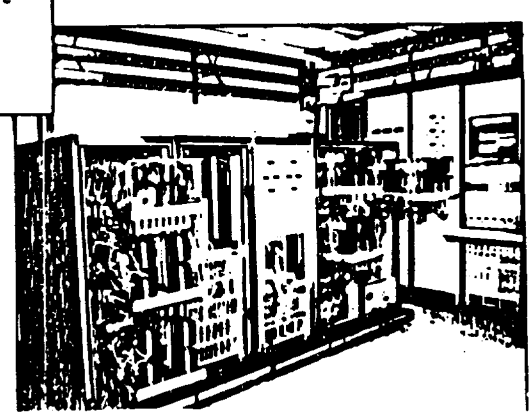
SPACE PLATFORMS TECHNOLOGY PROGRAM

EARTH ORBITING PLATFORMS
(INCLUDES SPACE STATIONS)

OAET — POWER AND THERMAL MANAGEMENT

HIGH FREQUENCY POWER TECHNOLOGY





SPACE STATION FREEDOM PMAD TEST BED

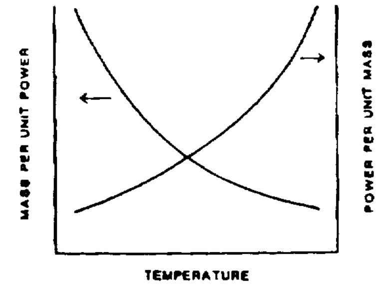
SPACE PLATFORMS TECHNOLOGY PROGRAM

EARTH ORBITING PLATFORMS

(INCLUDES SPACE STATIONS)

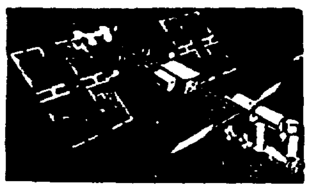
OAET — POWER AND THERMAL MANAGEMENT

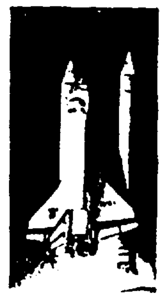
HIGH TEMPERATURE POWER TECHNOLOGY



GOALS

- REDUCE RADIATOR WEIGHT IN SPACE SYSTEMS BY RAISING OPERATING TEMPERATURE FROM 100°C TO 300°C
- HOSTILE ENVIRONMENT TOLERANCE
- IMPROVE RELIABILITY AND LIFETIME
- HIGHER ENERGY DENSITIES
- LESS THERMAL MANAGEMENT REQUIREMENTS
- REDUCE LAUNCH COST





TECHNOLOGICAL DEVELOPMENTS

- ADVANCED MATERIALS: DIELECTRICS, INSULATION, SEMICONDUCTOR, MAGNETICS
- COMPONENTS: CAPACITORS, INDUCTORS, SWITCHES, TRANSISTORS, CABLES, TRANSFORMERS, CIRCUIT BOARDS, INVERTERS, GENERATORS, COMPUTERS

APPLICATIONS

- SPACE EXPLORATION AND DOD SYSTEMS
- SPACE NUCLEAR POWER
- ADVANCED AND CONVENTIONAL AIRCRAFT

1-87 pm

SPACE PLATFORMS TECHNOLOGY PROGRAM

EARTH ORBITING PLATFORMS

(INCLUDES SPACE STATIONS)

OAET — POWER AND THERMAL MANAGEMENT

CVD DIAMOND FILMS FOR HIGH POWER ELECTRONICS

SYNTHESIS

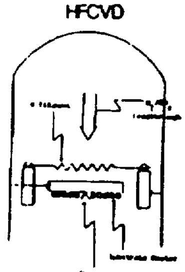
CHARACTERIZATION

& MODELLING

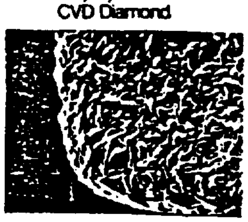
OF CVD DIAMOND

WILL ENABLE:

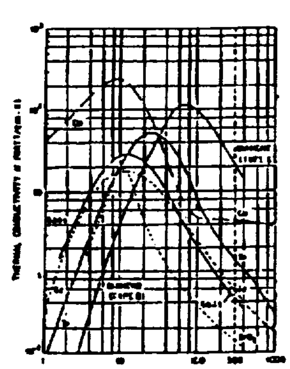
HFCVD

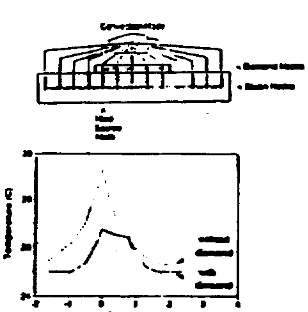


Polycrystalline CVD Diamond



Thermal Conductivity





- o More Efficient Heat Spreaders
- o Lower Device Operating Temperatures
- o Increased Device Reliability/Lifetime
- o Increased Specific Power
- o Elaborate Device Geometries

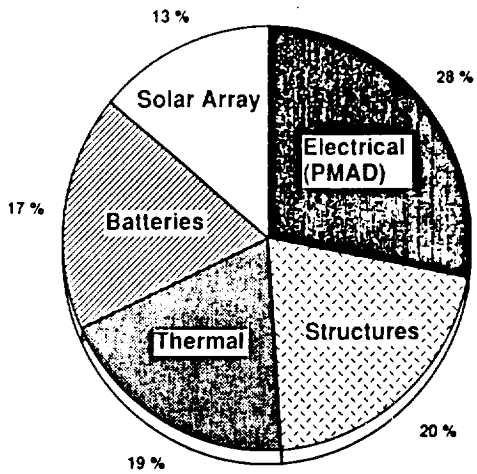
RC-ITP91.01-30 pm

SPACE PLATFORMS TECHNOLOGY PROGRAM

EARTH ORBITING PLATFORMS
(INCLUDES SPACE STATIONS)

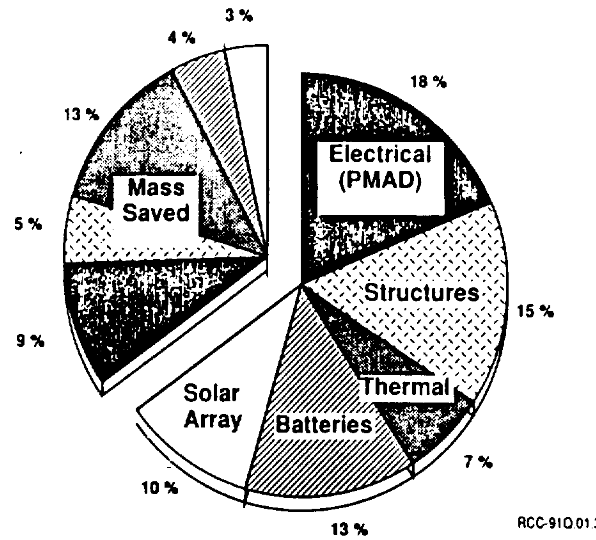
OAET — POWER AND THERMAL MANAGEMENT

Efficient, High Temperature Power for Growth Station



Present Power System Mases

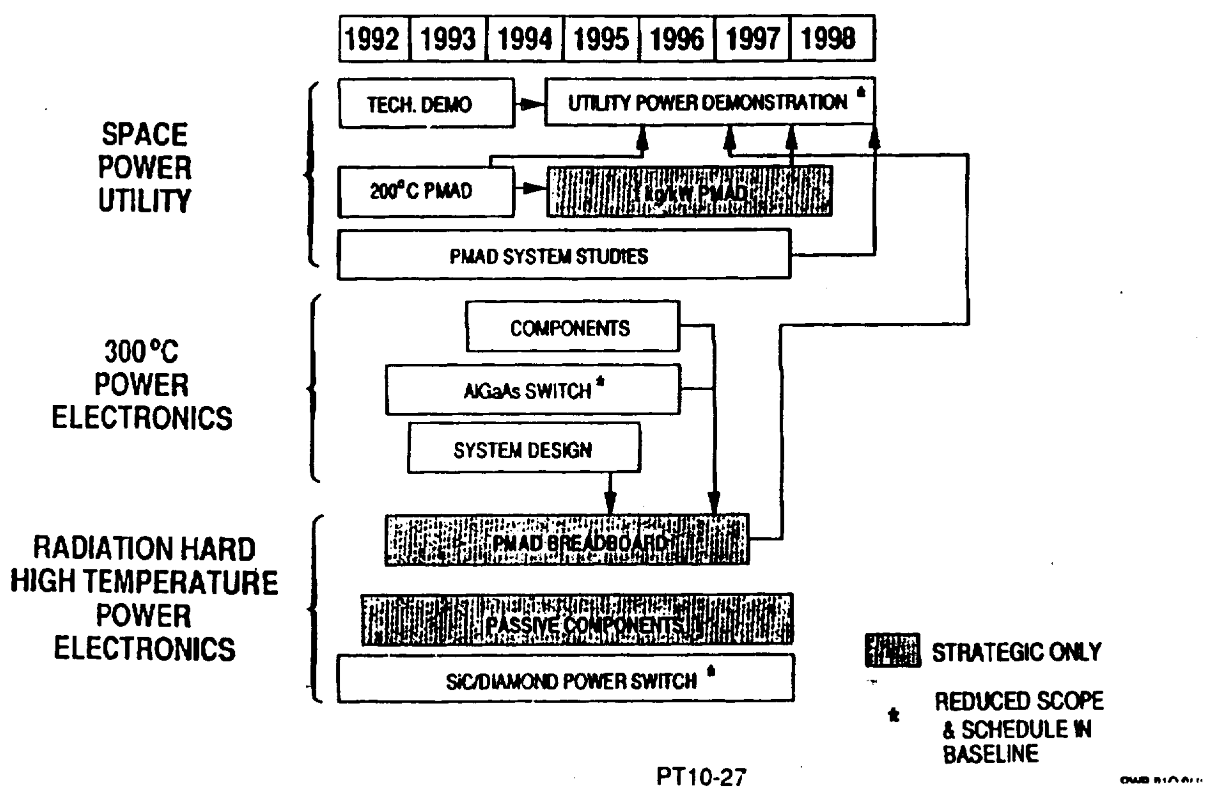
Fault Tolerant AC and Advanced PMAD Components



EARTH ORBITING PLATFORMS
(INCLUDES SPACE STATIONS)

OAET — POWER AND THERMAL MANAGEMENT

SPACE-UTILITY/HIGH TEMPERATURE PMAD ROADMAP/SCHEDULE



Project Overview and Resources

Technology Program: Space Platforms
Technology Area: Earth Orbiting Platforms
Technology Element: Power
Technology Sub-Element: Power Mgmt & Control (Solar Dynamic)

WBS No.: 694-11-03

Milestones:

- 1994 Select PMAD architecture
- 1996 Demo prototype PMAD brassboard
- 1997 Demo mixed source operation
- 1998 Complete PMAD testbed
- 1999 Demo autonomous control, fault tolerance, and reconfiguration

	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000
R&D Resources:	0	0	0.4	0.8	1.2	1.2	1.3	1.2	0	0
C of F ($M):	0	0	0	0	0.2	0.2	0.3	0	0	0

SPACE PLATFORMS TECHNOLOGY PROGRAM
EARTH ORBITING PLATFORMS
(INCLUDES SPACE STATIONS)
OAET
POWER AND THERMAL MANAGEMENT

Project Overview and Resources

Technology Program: Space Platforms
Technology Area: Earth Orbiting Platforms
Technology Element: Power
Technology Sub-Element: Power Managemt. & Control (Photovoltaic)

WBS No.: 694-11-07

Milestones:

- 1994 Select PMAC architectures; demo GIC EMI shielded electronics box
- 1995 Demo smart, long life components (PIC and other)
- 1996 Demo monolithic circuits
- 1997 Demo fault tolerant PMAC breadboard
- 1997 Demo 200-600 C components/circuits
- 1998 Advanced EPSAT code
- 1999 Demo smart power backbone avionics system

	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000
R&D Resources:	0	0	1.2	2	2.9	3.5	4.1	3.9	0	0
C of F ($M):	0	0	0	0	0	0.3	0.3	0.4	0	0

SPACE PLATFORMS TECHNOLOGY PROGRAM

EARTH ORBITING PLATFORMS

(INCLUDES SPACE STATIONS)

OAET — POWER AND THERMAL MANAGEMENT

THERMAL MANAGEMENT

OBJECTIVES

- DEVELOP THE THERMAL MANAGEMENT TECHNOLOGY FOR ADVANCED HIGH CAPACITY AND HIGH PERFORMANCE THERMAL MANAGEMENT SYSTEMS FOR FUTURE NASA SPACE MISSIONS
- ENHANCE THE UNDERSTANDING OF FLUID BEHAVIOR AND DYNAMICS IN A REDUCED GRAVITY ENVIRONMENT TO ESTABLISH RELIABLE PREDICTIVE MODELS AND DATA BASES FOR THE DEVELOPMENT OF ADVANCED SPACE SYSTEMS. INTERESTS INCLUDE TWO-PHASE FLOW REGIME, LIQUID/VAPOR INTERFACES AND FLOW BOILING
- DEVELOP, ANALYZE, AND TEST VARIOUS THERMAL ENERGY MANAGEMENT CONCEPTS AND COMPONENTS FOR APPLICATION TO FUTURE SPACECRAFT AND SPACE FACILITIES

TECHNOLOGY AREAS

- FILM CONDENSATION, FLOW BOILING AND TWO-PHASE REGIMES
- ADVANCED RADIATORS
- HEAT PIPES
- HEAT PUMPS

RC-ITP91 01-93 pm

SPACE PLATFORMS TECHNOLOGY PROGRAM

EARTH ORBITING PLATFORMS

(INCLUDES SPACE STATIONS)

OAET — POWER AND THERMAL MANAGEMENT

THERMAL MANAGEMENT

- THE THERMAL MANAGEMENT SUB-ELEMENT WILL SUPPORT THE PLATFORM POWER AND THERMAL MANAGEMENT BY PURSUING AN INTEGRATED PROGRAM WHICH FOCUSES ON THE FOLLOWING ACTIVITIES:
  - MODULAR HEAT PUMPS (100 W TO 1 kW)
  - CRYOGENIC HEAT PIPES (60 - 80 K RANGE)
  - LIGHTWEIGHT MATERIALS
  - MINI CAPILLARY PUMPED LOOPS (<500 W)

RC-ITP91 01-88 pm

BENEFITS TO SPACE STATION
- THERMAL MANAGEMENT -

THE THERMAL MANAGEMENT TECHNOLOGIES DEVELOPED IN THIS ACTIVITY WILL PROVIDE THE FOLLOWING BENEFITS:

- HEAT PUMPS - AS AN INTERMEDIARY BETWEEN A CENTRAL THERMAL BUS AND A LOAD, A HEAT PUMP COULD ALLOW INDEPENDENT TEMPERATURE CONTROL. THE SECOND, LOWER TEMPERATURE BUS, WOULD NOT BE NEEDED. ALTERNATIVELY, LOWER TEMPERATURES ARE POSSIBLE.
- CRYOGENIC HEATS PIPES - THESE COULD SERVE AS AN INTERFACE BETWEEN CRYOGENIC SENSORS AND A CENTRAL BANK OF CRYOCOOLERS. THE NUMBER OF SUCH COOLERS NEEDED WOULD THUS BE REDUCED, AND THEIR ASSOCIATED VIBRATION AND EMI SEPARATED FROM THE SENSORS.
- LIGHT-WEIGHT MATERIALS - WEIGHT REDUCTION
- MINI CAPILLARY PUMPED LOOPS - COULD PROVIDE INDEPENDENT COOLING FOR INSTRUMENTS

RC-ITP91 01-73.pm

Project Overview and Resources

<u>Technology Program:</u> Space Platforms — WBS No.: 694-11-01
<u>Technology Area:</u> Earth Orbiting Platforms
<u>Technology Element:</u> Power
<u>Technology Sub-Element:</u> Thermal Management (Photovoltaic)

<u>Milestones:</u>

1994	Demo mini CPL thermal control loop
1995	Demo 50% improvement (watt-meter basis) in advanced cryoheat pipes on ground
1995	Demo 33% weight reduction in thermal components by using lightweight materials
1996	Demo advanced heat pump designs suitable for micro gravity applications, with goal of 3x current performanct factor
1996	Design cryo CPL thermal control loop
1997	Flight test advanced cryo heat pipes
1997	Demo ground test of advanced cryo CPL
1998	Validate cryo heat pipe models
1998	Flight test advanced heat pumps
1999	Validate heat pump models
2000	Flight test cryo CPL thermal control loop

	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000
R&D Resources:	0	0	0.6	0.8	1.3	1.3	1.4	1.3	0	0
C of F ($M):	0	0	0	0	0.5	0.2	0	0	0	0

Project Overview and Resources

Technology Program:	Space Platforms	WBS No.: 694-11-04
Technology Area:	Earth Orbiting Platforms	
Technology Element:	Power	
Technology Sub-Element:	Thermal Management (Solar Dynamic)	

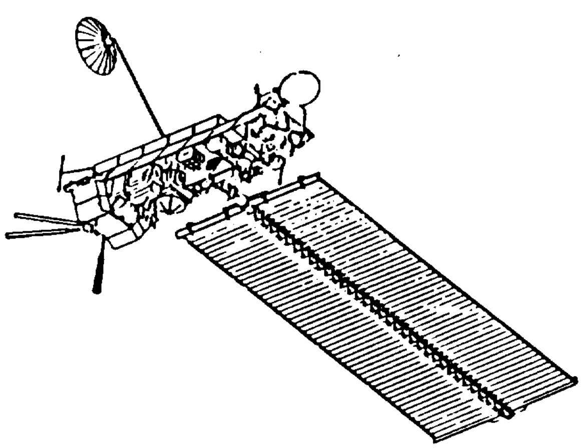
Milestones:

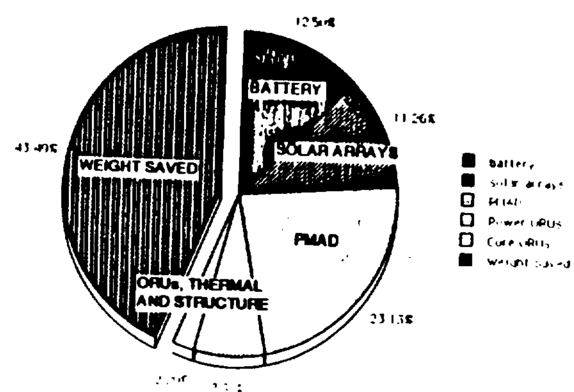
1994	Demo mini CPL thermal control loop
1995	Demo 50% improvement for advanced cryoheat pipes in ground test
1995	Demo 33% weight reduction for thermal components made from lightweight materials
1996	Demo advanced heat pump (for 500 W-5 kW range), 3X performance improvement
1997	Flight test cryoheat pipes
1997	Demo ground test of cryo CPL ground loop
1998	Validate cryo heat pipe models
1998	Flight test of advanced heat pumps
1999	Validate heat pump models
2000	Flight test of cryo CPL thermal loop

	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000
R&D Resources:	0	0	0.4	0.6	1.0	1.0	1.0	1.0	0	0
C of F ($M):	0	0	0	0	0.1	0.3	0.3	0	0	0

SPACE PLATFORMS TECHNOLOGY PROGRAM
EARTH ORBITING PLATFORMS
(INCLUDES SPACE STATIONS)
OAET
POWER AND THERMAL MANAGEMENT

ELECTRICAL POWER SYSTEM WEIGHTS WITH ADVANCED TECHNOLOGIES





ADVANCED POWER SYSTEM TECHNOLOGIES CAN SAVE 645 kg (1420 lb) IN THE ELECTRICAL POWER SYSTEM

SPACE PLATFORMS TECHNOLOGY PROGRAM

EARTH ORBITING PLATFORMS

(INCLUDES SPACE STATIONS)

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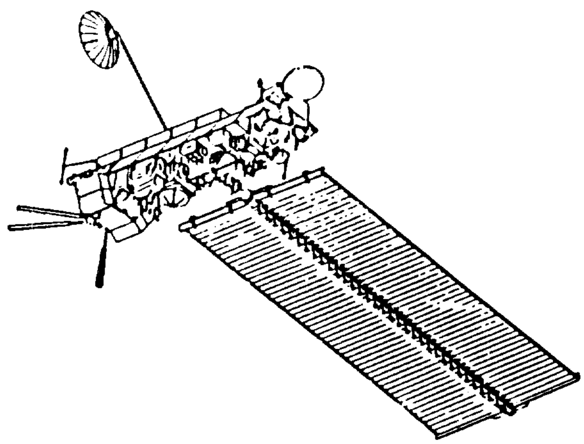
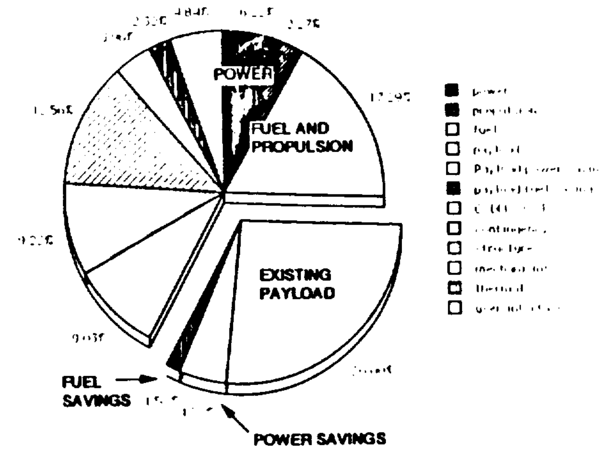
POLAR PLATFORM WEIGHT WITH ADVANCED TECHNOLOGIES





NEW TECHNOLOGIES SAVE 850 Kg (1870 lbs.)
ALLOWS~32% OF MASS TO BE PAYLOAD

SPACE PLATFORMS TECHNOLOGY PROGRAM

EARTH ORBITING PLATFORMS

(INCLUDES SPACE STATIONS)

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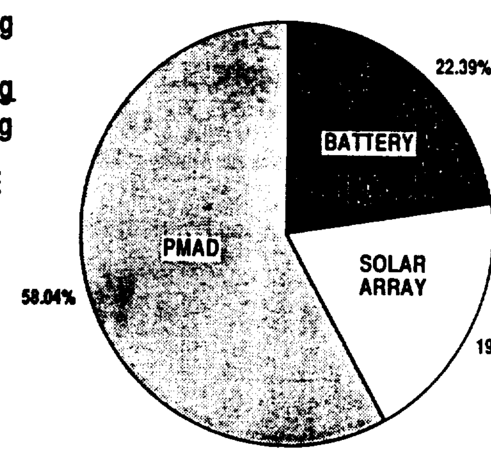
TDRSS

- NEW TECHNOLOGY ALLOWS 138% MORE POWER FOR THE SAME MASS
- FOR 422.3 kg, NEW TECHNOLOGY GIVES 5729 WATTS

SOLAR ARRAY MASS	82.67 kg
BATTERY MASS	94.53 kg
PMAD MASS	245.08 kg
	422.28 kg

- ADDITIONAL 3319 WATTS OF POWER AVAILABLE WITH NEW TECHNOLOGY FOR THE SAME MASS



5,729 WATTS
BOL POWER

RC-ITP91.01-70 pm

SPACE PLATFORMS TECHNOLOGY PROGRAM

EARTH ORBITING PLATFORMS
(INCLUDES SPACE STATIONS)

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Milestones:

1997 (2) Demo 300 W/sq. m PV concentrator module (>50 W)
1997 (2) Ground demo, integrated 2 kW solar dynamic system
1996 (2) Demo advanced heat pump designs suitable for micro gravity
1996 (2) Demo prototype PMAD brassboard
1996 (1) Complete enhanced EPSAT environmental interaction model (LEO, GEO, MEO, POLAR); ground test cryo CPL
1996 (1) Demo 300 Wh/kg PV blanket; 100 Wh/kg InP concentrator module
1995 (1) Demo 100 Wh/kg boiler plate cells to 1000 cycles (GEO); complete design of cryo CPL for sensors
1995 (1) Demo 35% reduction in weight of thermal components
1994 (1) Demo G/C shielded electronics box
1997 (1) Demo ground test of advanced cryo CPL
1997 (1) Demo advanced PMAC integrated avionics system; validate heat pump models
1998 (1) Demo 1-2 kg/sq. m thermal management system
1998 (2) Flight test heat pumps
1998 (2) Complete advanced EPSAT
1999 (2) Demo SSF power TD&C facility
1999 (1) Demo 100 Wh/kg battery (flightweight)
2000 (1) Demo durable high temperature electronics subsystem (200-600 C)
2000 (1) Flight test cryo CPL

	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000
R&D Resources:	0	0	0	0	0	0	0	0	0	0
Reserves:	0	0	0	0	0	0	0	0	0	0
Total R&D:	0	0	5.1	10.2	13.5	14.3	14.7	14	0	0
C of F ($M):	0	0	0	0	0.8	1	0.9	0.4	0	

SPACE PLATFORMS TECHNOLOGY PROGRAM

EARTH ORBITING PLATFORMS
(INCLUDES SPACE STATIONS)

OAET — POWER AND THERMAL MANAGEMENT

694-11 SPACE PLATFORM TECHNOLOGY - EARTH ORBITING PLATFORMS

	694-11	1993	1994	1995	1996	1997	1998	1999
THERMAL (PV)	-01	0.6	0.8	1.3	1.3	1.4	1.3	
SOLAR DYNAMIC	-02	1.2	3.5	3.6	3.4	3.0	1.9	
PMAD (SD)	-03	0.4	0.8	1.2	1.2	1.2	1.2	
THERMAL (SD)	-04	0.4	0.6	1.0	1.0	1.0	1.0	
PHOTOVOLTAIC	-05	0.6	1.3	1.9	2.3	2.5	3.3	
ENERGY STORAGE	-06	0.7	1.2	1.6	1.6	1.4	1.4	
PMAD (PV)	-07	1.2	2.0	2.9	3.5	4.1	3.9	
TOTALS		5.1	10.2	13.5	14.3	14.7	14.0	

SPACE PLATFORMS TECHNOLOGY PROGRAM

EARTH ORBITING PLATFORMS

(INCLUDES SPACE STATIONS)

OAET — POWER AND THERMAL MANAGEMENT

CONCLUSIONS

- THERE ARE BASE TECHNOLOGIES THAT COULD BE MADE AVAILABLE FOR ORBITING PLATFORMS
  - ADVANCED PHOTOVOLTAIC SOLAR ARRAY (PLANAR AND CONCENTRATOR)
  - IMPROVED BATTERIES (NiH AND SODIUM)
  - SOLAR DYNAMIC SYSTEMS
  - IMPROVED PMAD
  - IMPROVED TMAD
- CODE RP IS CONTINUING TO SUPPORT ADVANCES IN POWER TECHNOLOGIES, INCLUDING:
  - HIGH EFFICIENCY, LIGHT-WEIGHT, RADIATION RESISTANT CELLS
  - ADVANCED CHEMICAL ENERGY STORAGE (NICKEL-HYDROGEN, BIPOLAR NICKEL-HYDROGEN)
  - POWER INTEGRATED CIRCUITS AND FAULT-TOLERANT AUTONOMOUS PMAD
- THESE TECHNOLOGIES CAN BE USED TO ACCOMPLISH SOME COMBINATION OF THE FOLLOWING:
  - REDUCE TOTAL MASS, OR
  - INCREASE PAYLOAD MASS
  - INCREASE POWER AVAILABLE BY UP TO 2x

RC-ITP91.01-71.pm

FOCUSED TECHNOLOGY: EARTH ORBITING PLATFORM

POWER AND THERMAL MANAGEMENT

SUMMARY

OAET

IMPACT:

- Enable exploitation of earth orbiting space by significant (> 2) improvements in mission critical power and thermal capacities fo
  - Wide range of users and missions: Unmanned/manned - Civil, Commercial,
  - Operating requirements: LEO → GEO, EQUATORIAL → POLAR
  - Power levels: 10's W → 10's kW

USER COORDINATION:

- Four element effort: (e.g., presently applied to EOS, ATDRSS, SSF)
  - Determining requirements of planned and proposed missions
  - Assessing impact of upgrade to base technologies
  - Addressing modification and adaptation of technology for mission unique requirements
  - Reviewing with program and project managers

OVERALL TECHNICAL AND PROGRAMMATIC STATUS:

- Basic understanding and development of technology progressing in all areas under base program
- No lack of technology

MAJOR TECHNICAL/PROGRAMMATIC ISSUES:

- Absence of focused effort to bring about:
  - Coordination with broad user and mission base
  - Coordination of multiple disciplines at system level
  - Timely development to level of implementation for flight
- Lack of means to get technology used

RC-ITP91.01-2.pm

THERMAL MANAGEMENT
- MILESTONES / SCHEDULE -

OAET

- DEMONSTRATE MINI-CAPILLARY PUMPED LOOPS — 1994
- DEMONSTRATE 2X-3X SOA FOR CRYOGENIC HEAT PIPES — 1995
- DEMONSTRATE 50% WEIGHT REDUCTION FOR THERMAL COMPONENTS — 1995
- DEVELOP SEVERAL ADVANCED HEAT PUMP DESIGNS, GOAL OF 3X SOA — 1996
- FLIGHT TEST ADVANCED CRYOGENIC HEAT PIPES — 1997
- VALIDATE CRYOGENIC HEAT PIPE MODELS — 1998
- FLIGHT TEST OF ADVANCED HEAT PUMPS — 1998
- VALIDATE HEAT PUMP MODELS — 1999

THERMAL MANAGEMENT
- MILESTONES / SCHEDULE -

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- FLIGHT TEST OF ADVANCED HEAT PUMPS — 1998
- VALIDATE HEAT PUMP MODELS — 1999

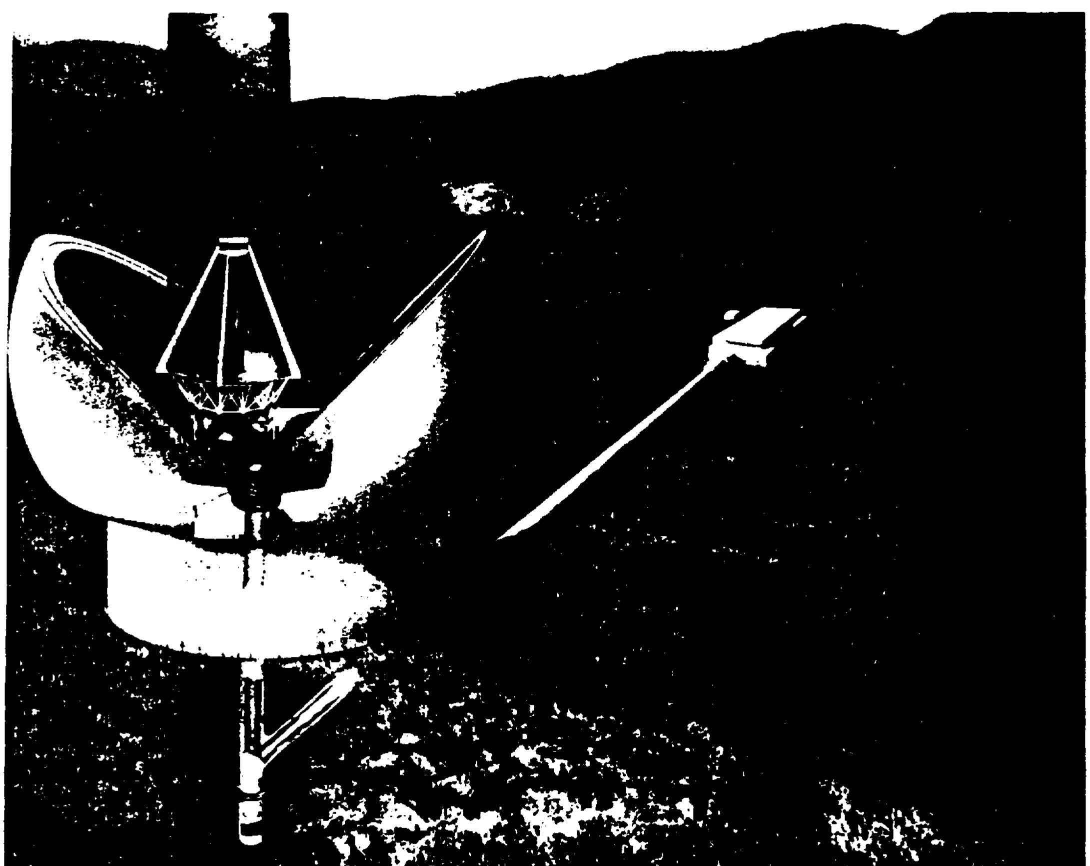
Project SELENE

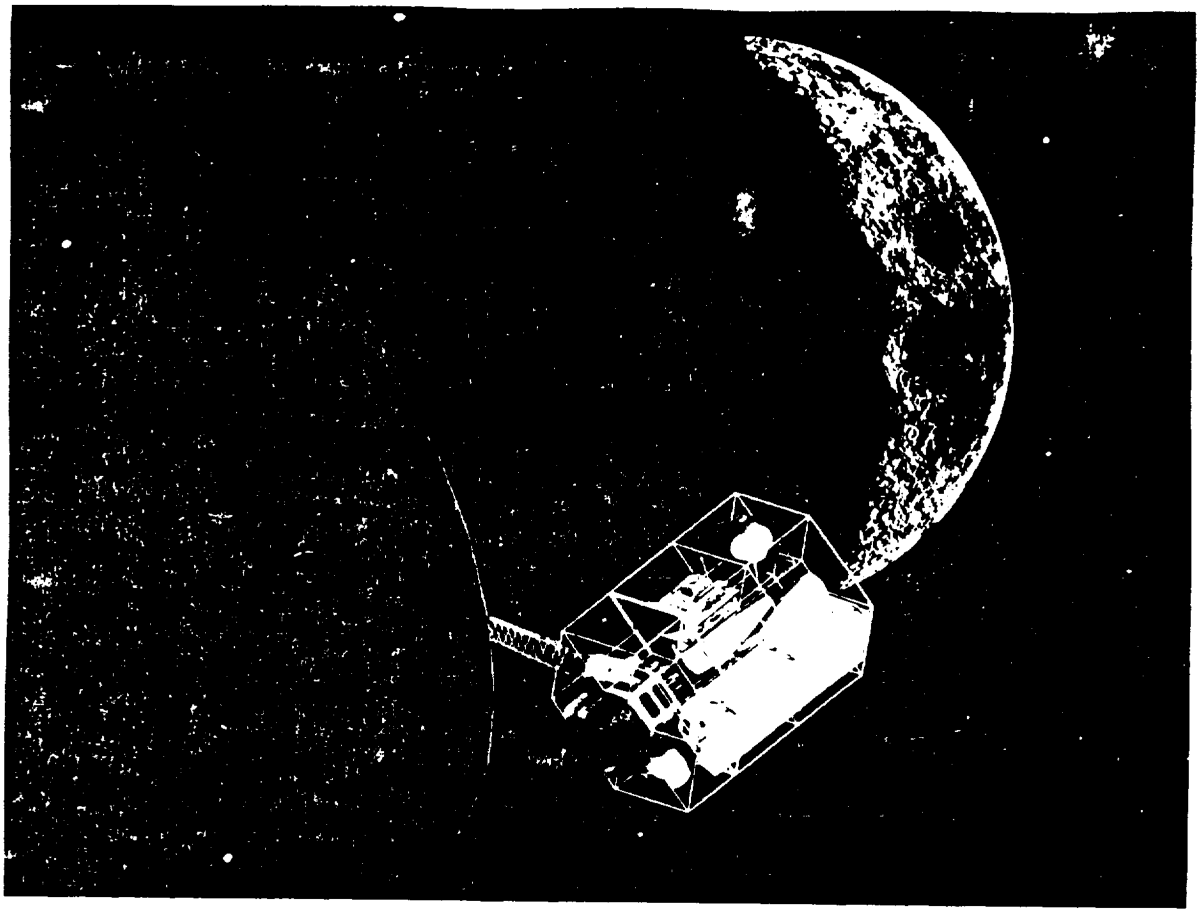
SpacE Laser Electric ENErgy

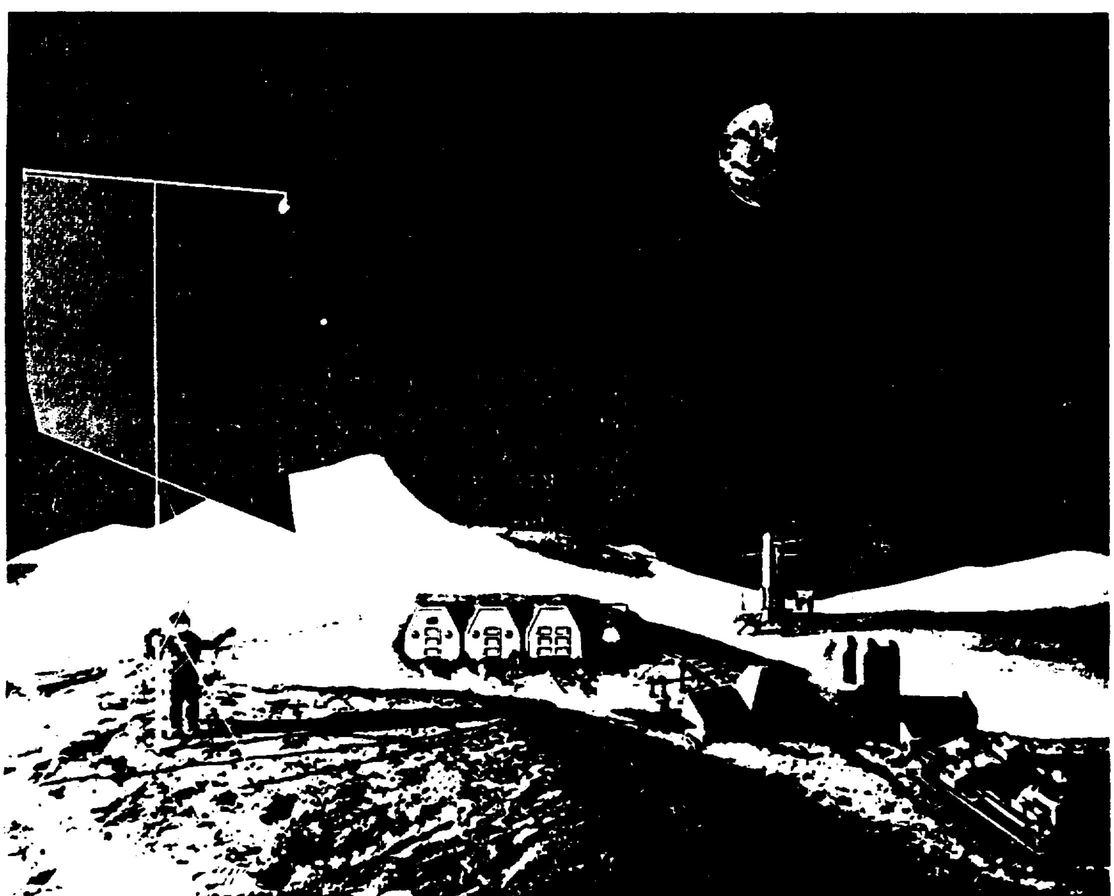
John D. G. Rather

NASA

"SELENE" is the ancient Greek name for the moon







TRANSPORTATION COSTS WITH MAXIMUM PAYLOADS
(1991 $ PER POUND)

OAET

VEHICLE	Earth to LEO		Earth to GEO		Earth to Lunar Surface	
	Cost	Max lbs.	Cost	Max lbs.	Cost	Max lbs.
Shuttle	$6,700	45,000	72,700	5,000*	50,000	10,000
Titan	$5,300	38,000	30,000	10,000	39,000	10,000
Shuttle Derived Vehicle	$3,400	89,000	25,000	10,000	34,000	10,000
National Launch Systems (NLS)	$3,000 $1,200	50,000 150,000	22,700 13,600	10,000 10,000	34,000 25,000	10,000 10,000

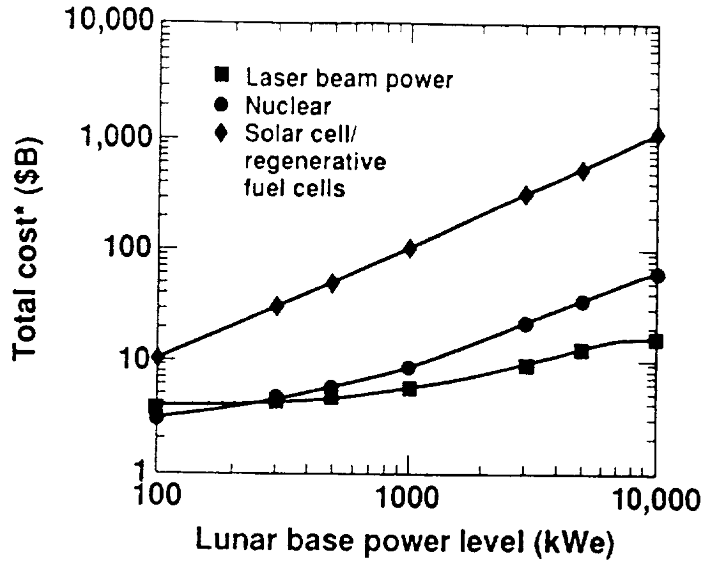
*Use of IUS with 500lb payload results in high $/lb relative to other options which assume a new upper stage with 10,000lb payload.

91-2251

High-Power Space Applications

- Electric propulsion for economical orbit raising (LEO to GEO, LEO to LLO, etc.)
- Power for lunar base
- Life support for large, manned space stations
- Industrial processes
- K-Band traffic monitoring and identification
  - Air traffic monitoring and identification
  - Ship traffic monitoring and identification
  - Clear air turbulence mapping
  - Defense
- Direct-broadcast TV transmission
- Advanced remote sensing

Comparison of costs of candidate lunar surface power architectures



* Costs include estimated transportation costs in 1990 dollars

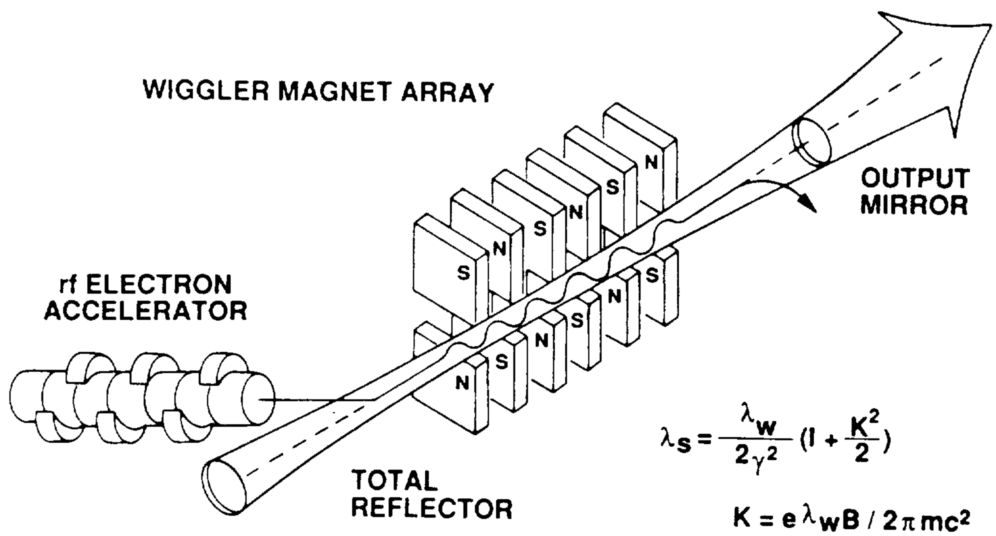
Refs:

(1) – NASA Lewis Research Center

(2) – NASA Pathfinder Program Plan

- **New optical technologies: The Key to implementation**

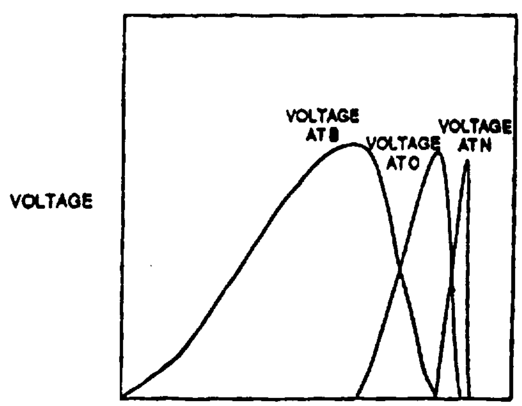
BASIC ELEMENTS OF A COMPTON - REGIME FREE ELECTRON LASER

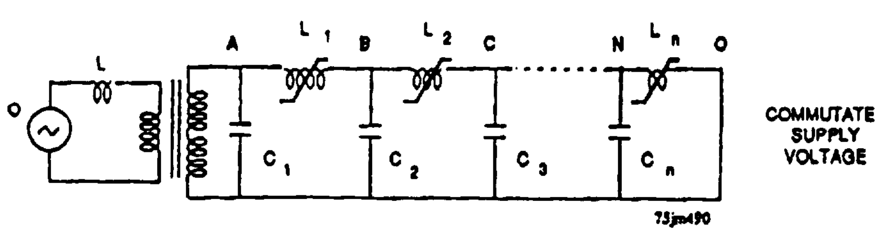


$$\lambda_s = \frac{\lambda_w}{2\gamma^2}\left(1 + \frac{K^2}{2}\right)$$

$$K = e\lambda_w B / 2\pi mc^2$$

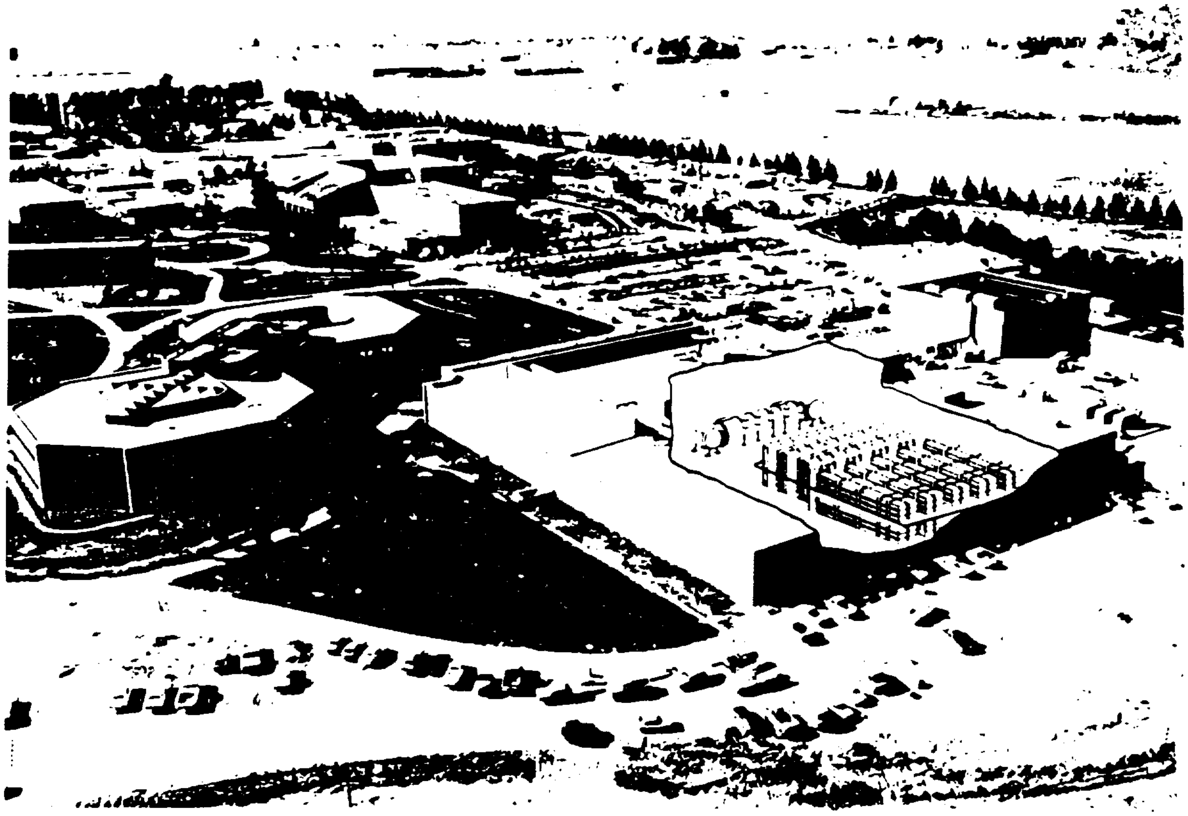
TYPICAL MAGNETIC SWITCH OPERATION





REFERENCE: SCIENCE RESEARCH LABORATORY

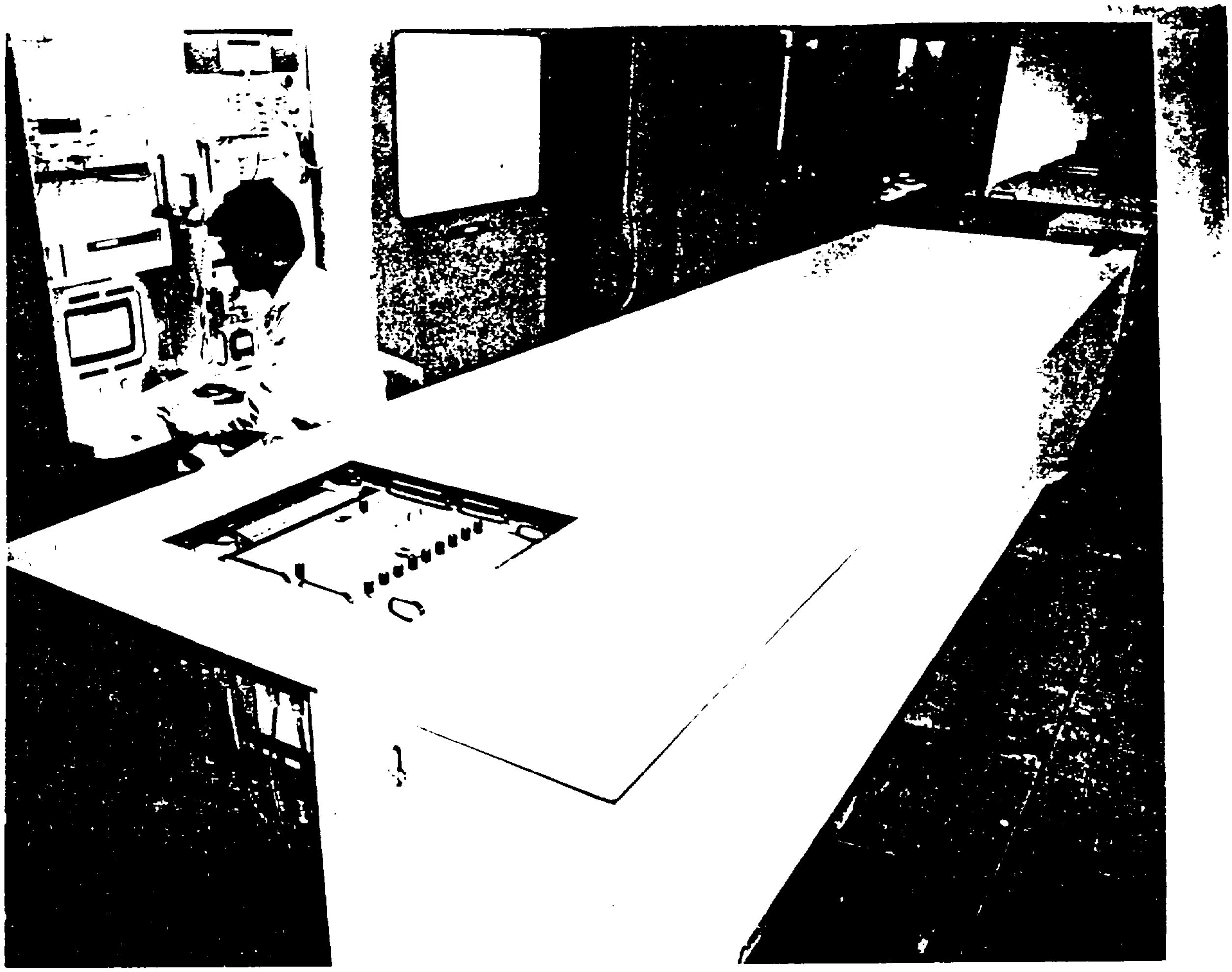
AVLIS Full-Scale Demonstration Facility



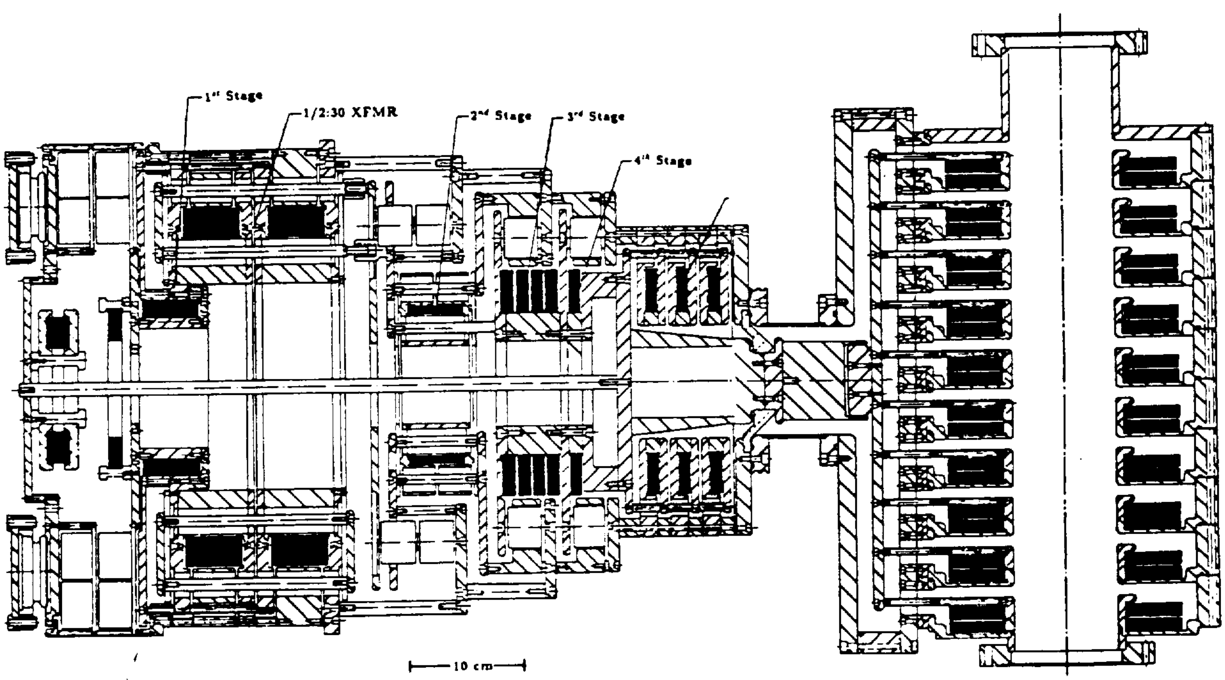
Copper laser corridors provide more than 8 kW of average power in around-the-clock operations

1.0.0590.1506
24 RSH

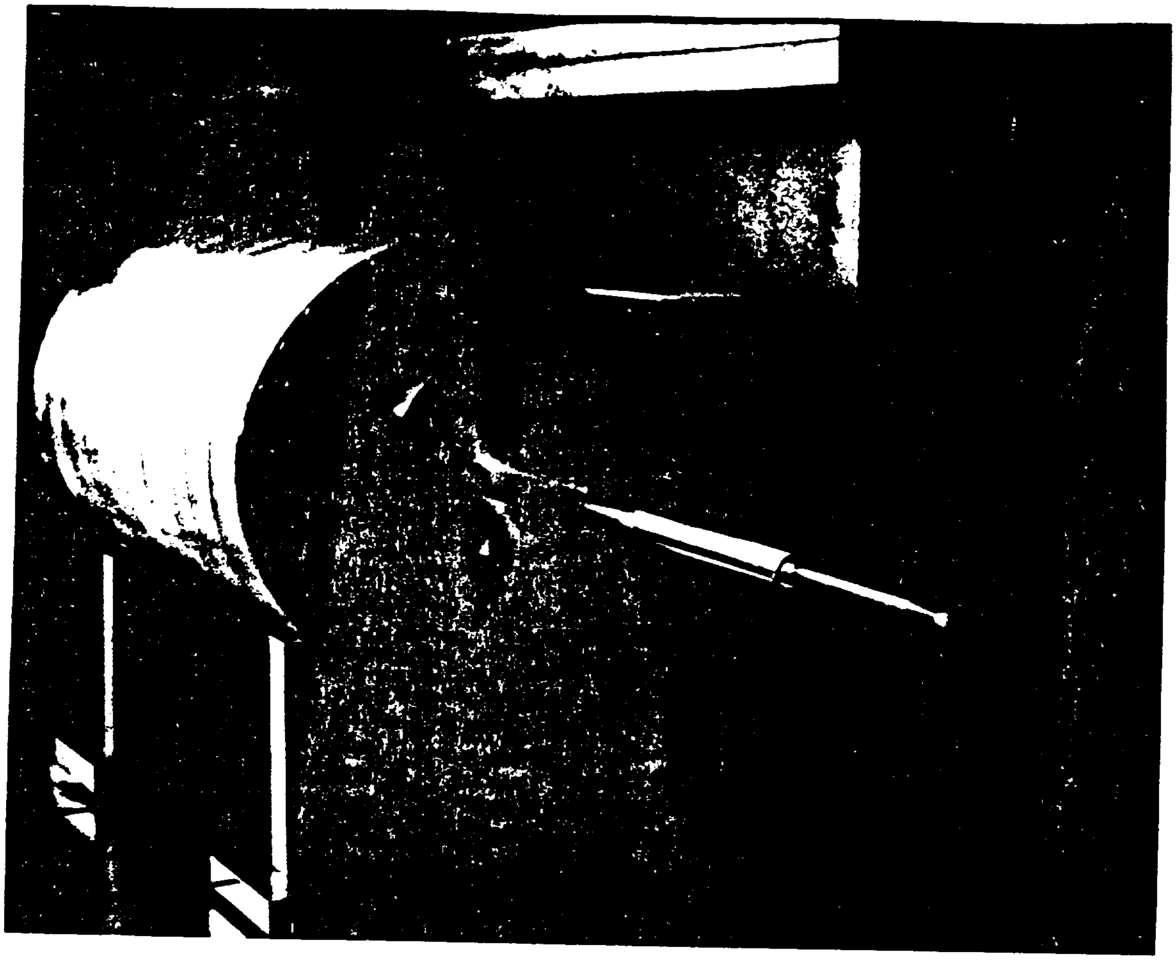
11/90

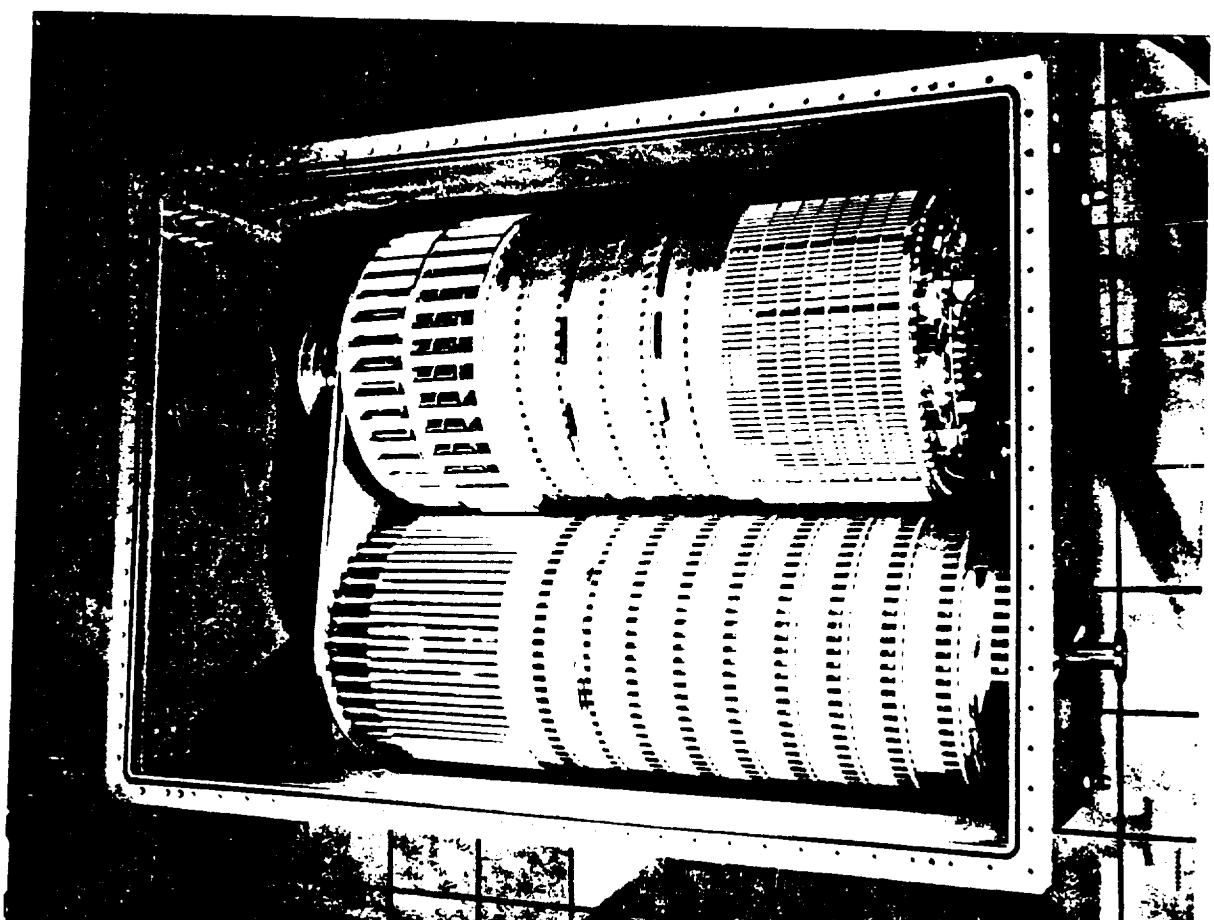


SNOMAD-V NONLINEAR MAGNETIC COMPRESSOR AND
1 MeV HIGH GRADIENT ACCELERATOR SECTION

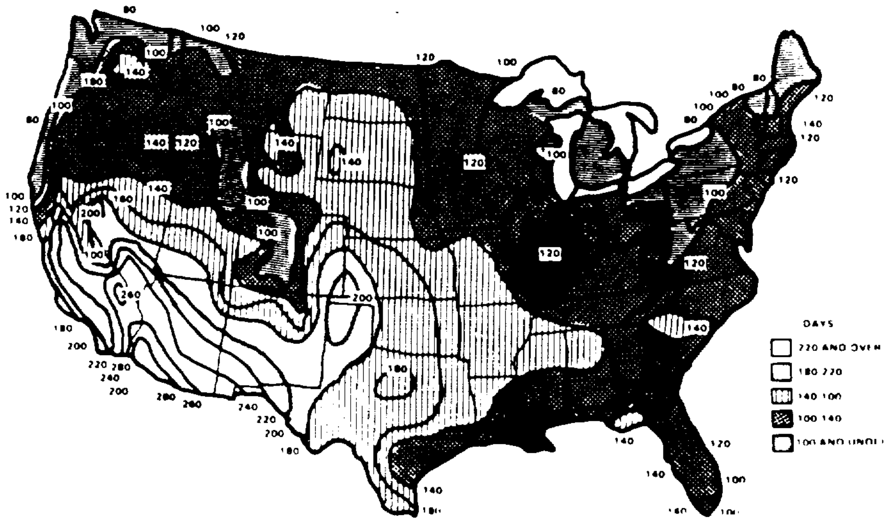


ORIGINAL PAGE IS
OF POOR QUALITY



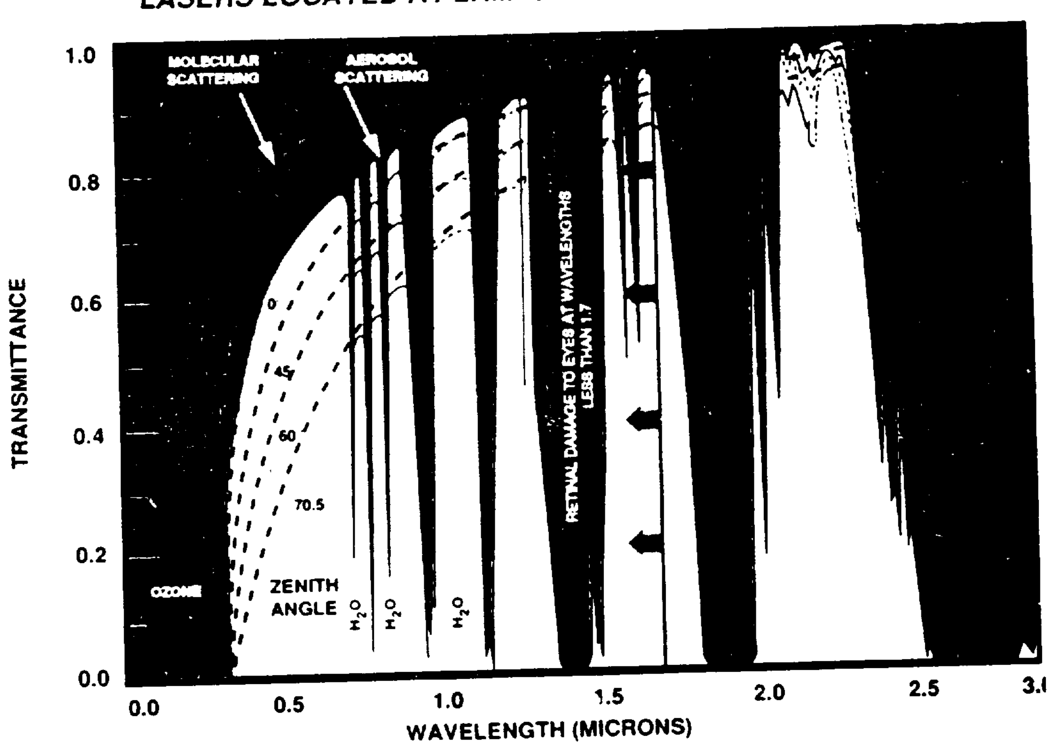


(U) LOCATION OF GROUND SITES DEPENDS PRIMARILY UPON AVERAGE ANNUAL NUMBER OF CLEAR DAYS

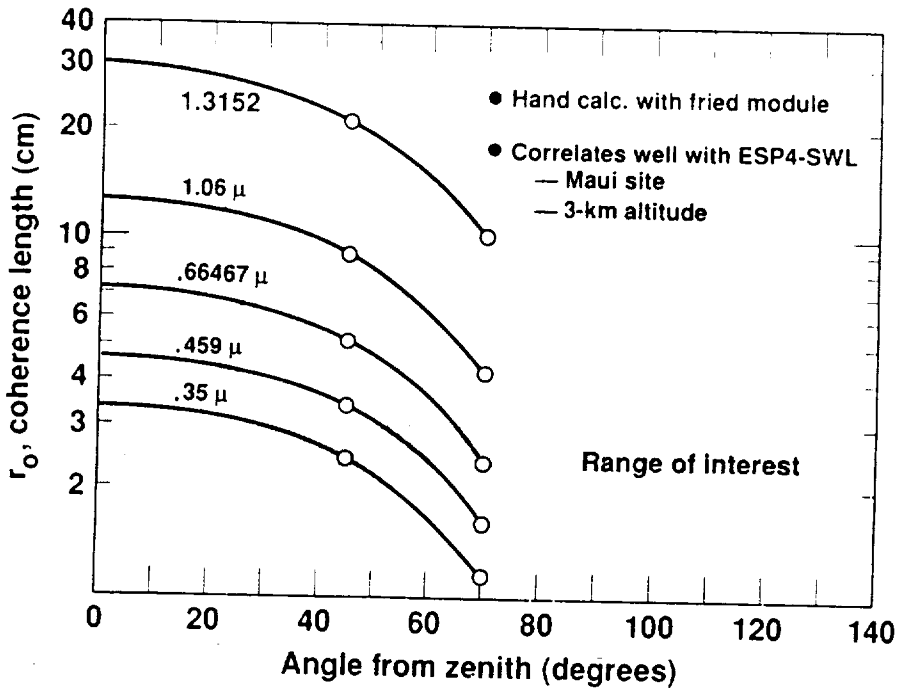


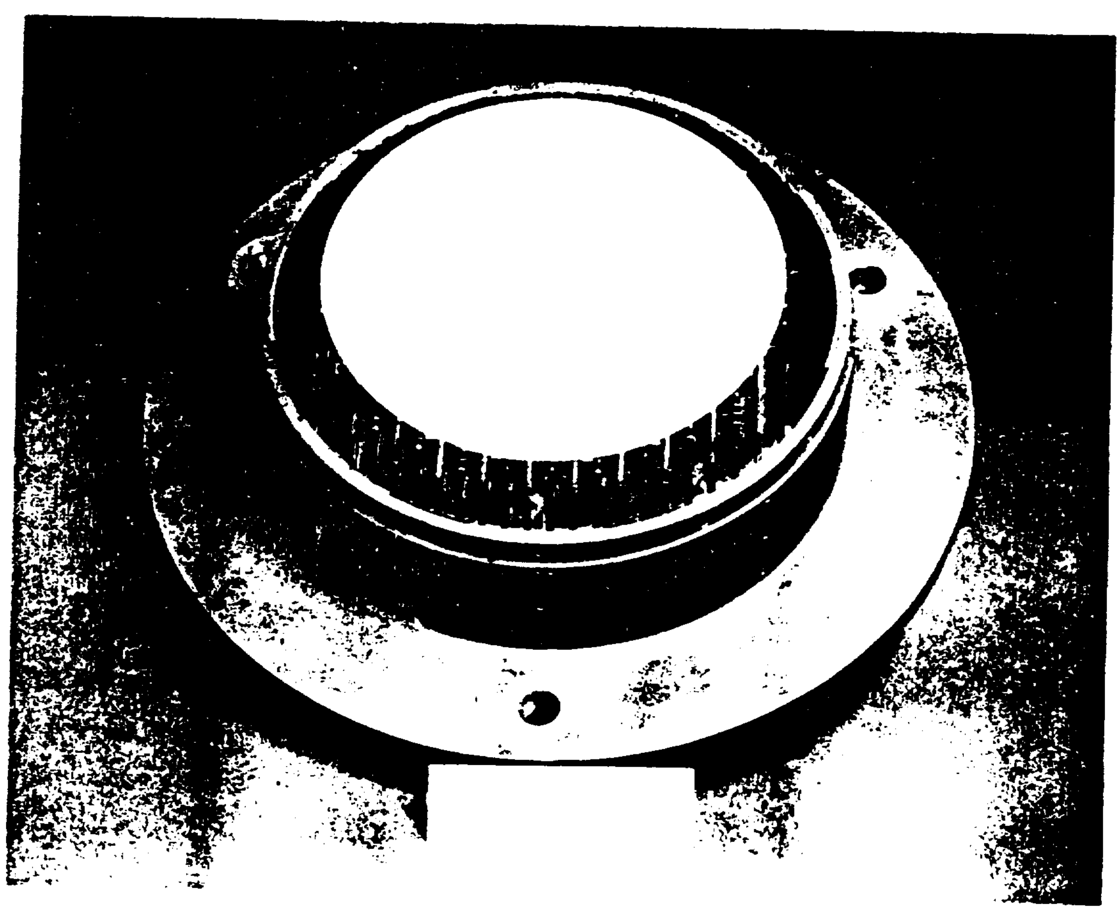
ATMOSPHERIC TRANSMITTANCE TO SPACE

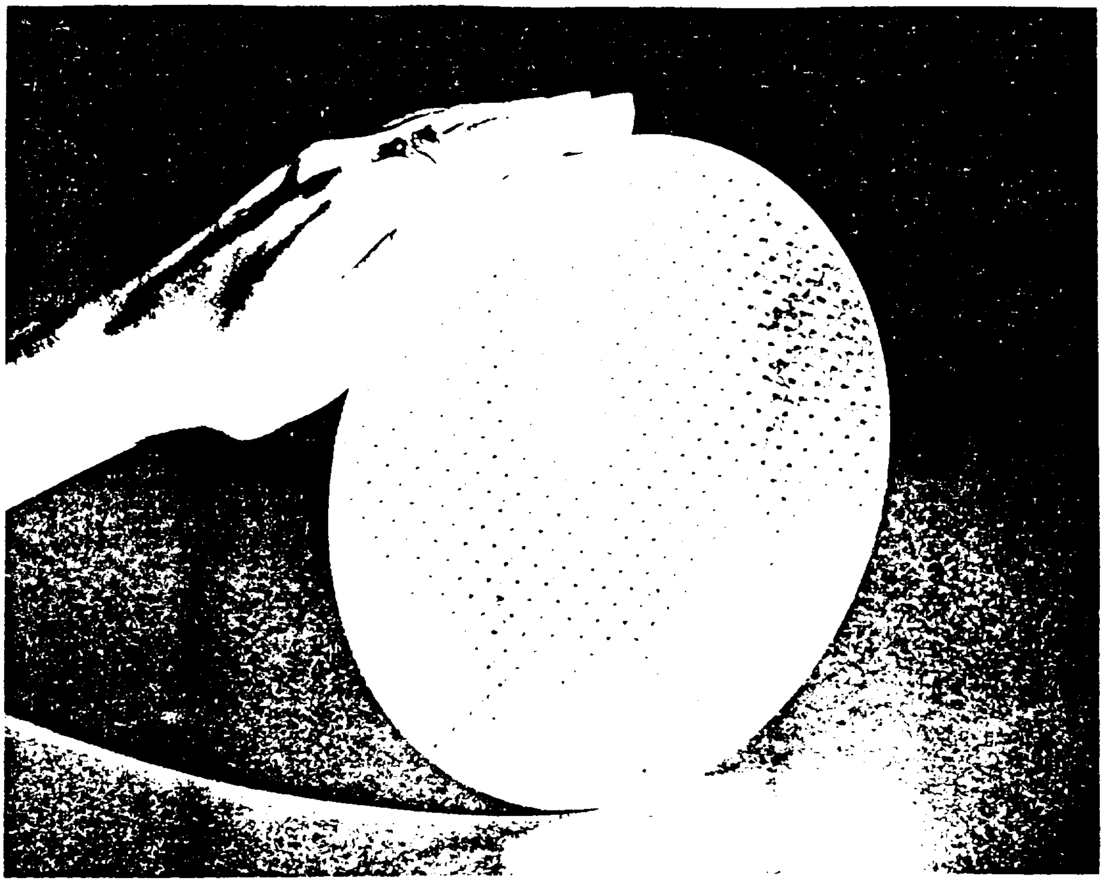
LASERS LOCATED AT 2KM ELEVATION ABOVE SEA LEVEL



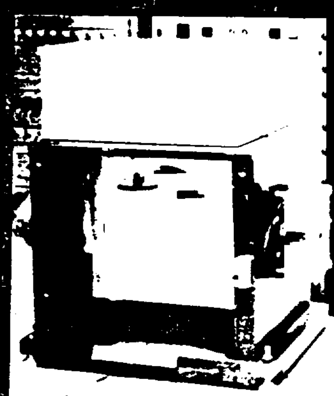
Turbulence coherence length as a function of wavelength and zenith angle

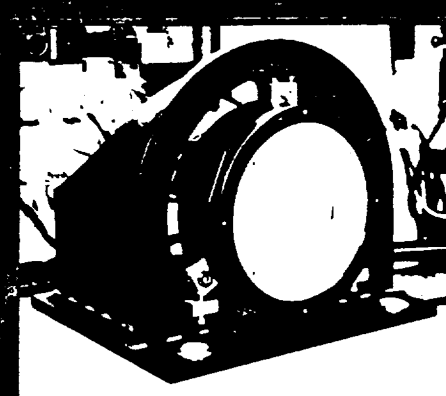






COOLED DEFORMABLE MIRRORS

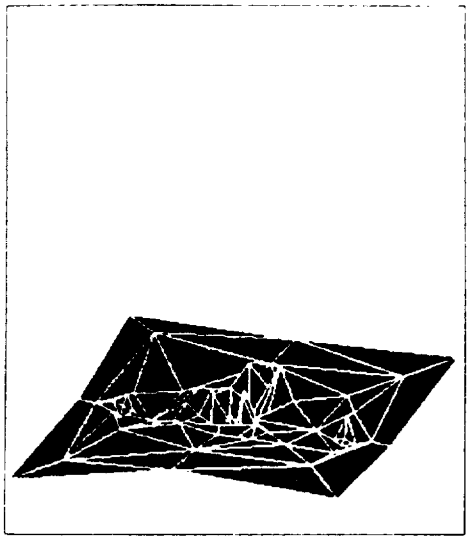




	UTOS HICLAS	ITEK LCDM
ACTUATORS:	69	241 (+ Two Guard Bands)
STROKE:	30 μm	4 μm
ACTIVE AREA:	16 cm DIAMETER	16 cm DIAMETER
SURFACE FIGURE:	~0.1 λrms(λ= 0.633 μm)	~0.02 λrms(λ= 0.633 μm)

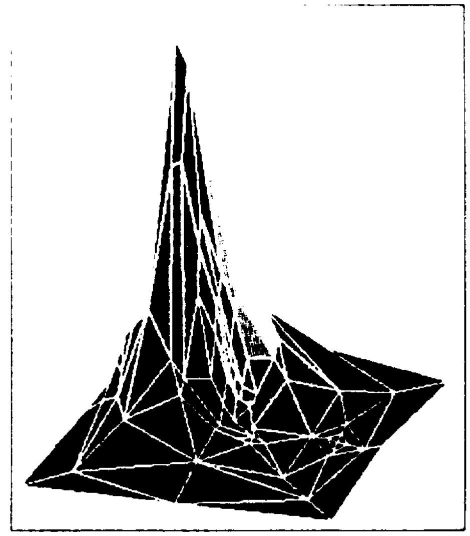
LACE Data 30 November 1990

SMC 182, Samples 180-184



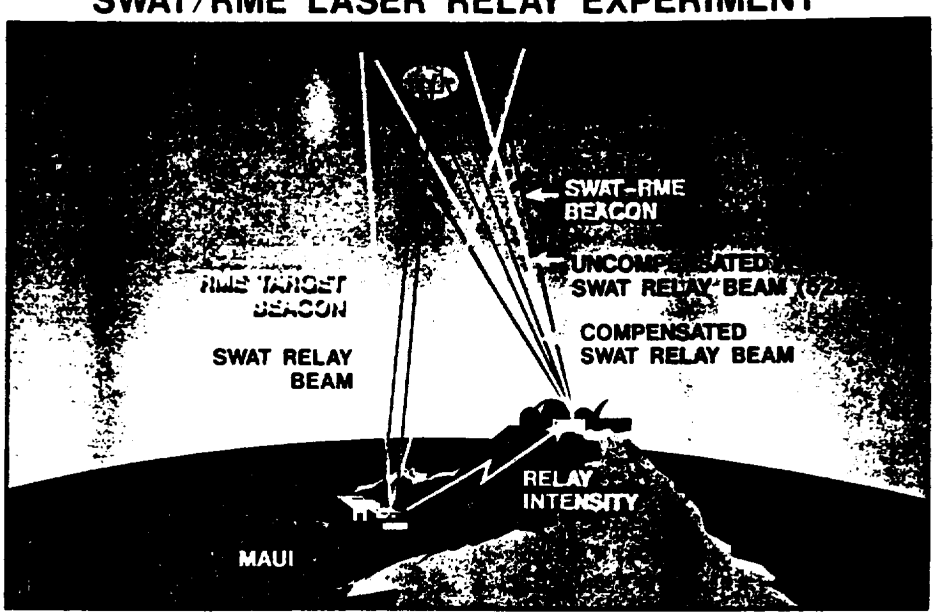
Uncompensated

SMC 181, Samples 160-164

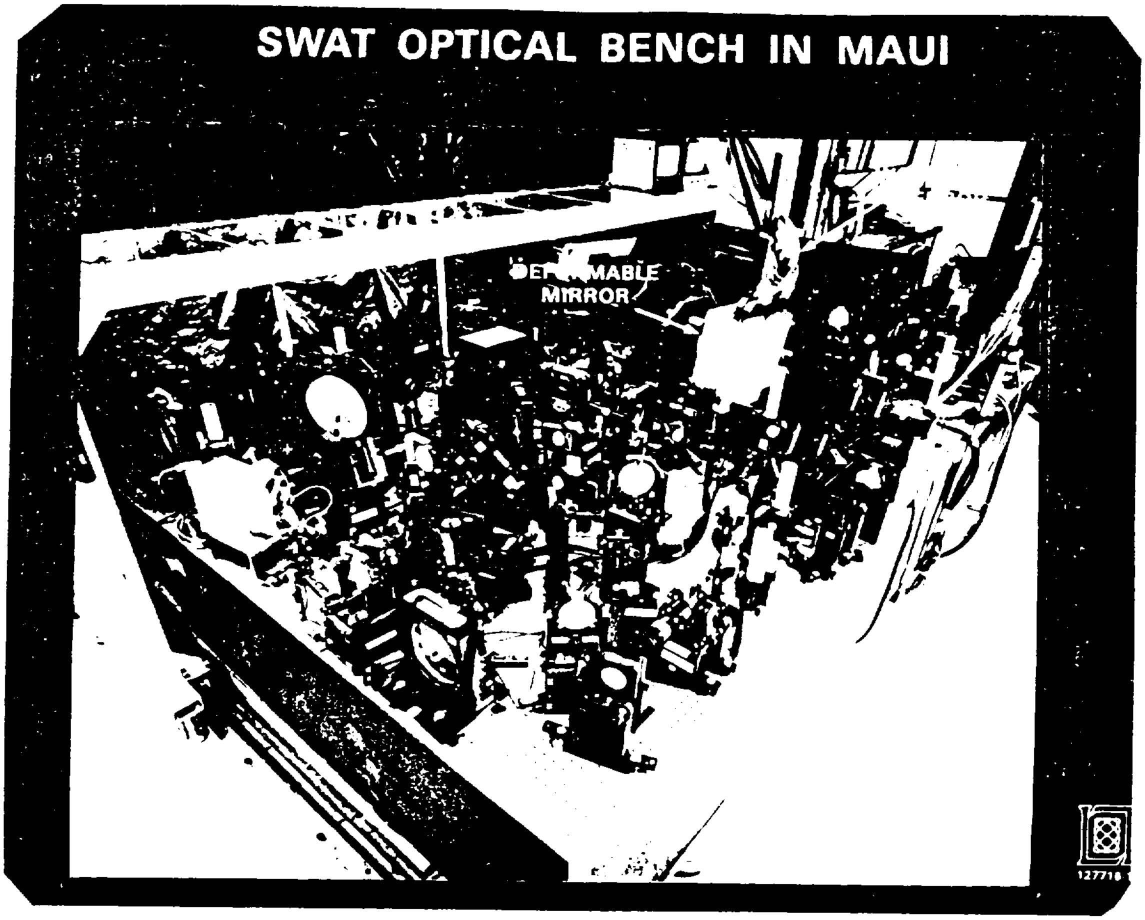


Compensated

SWAT/RME LASER RELAY EXPERIMENT



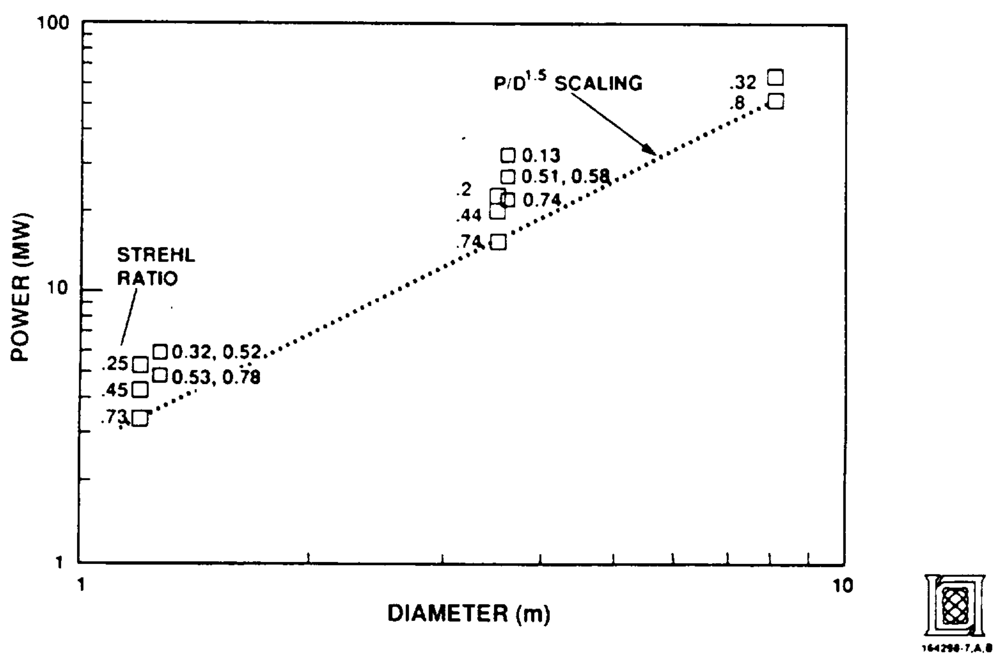
139167-1

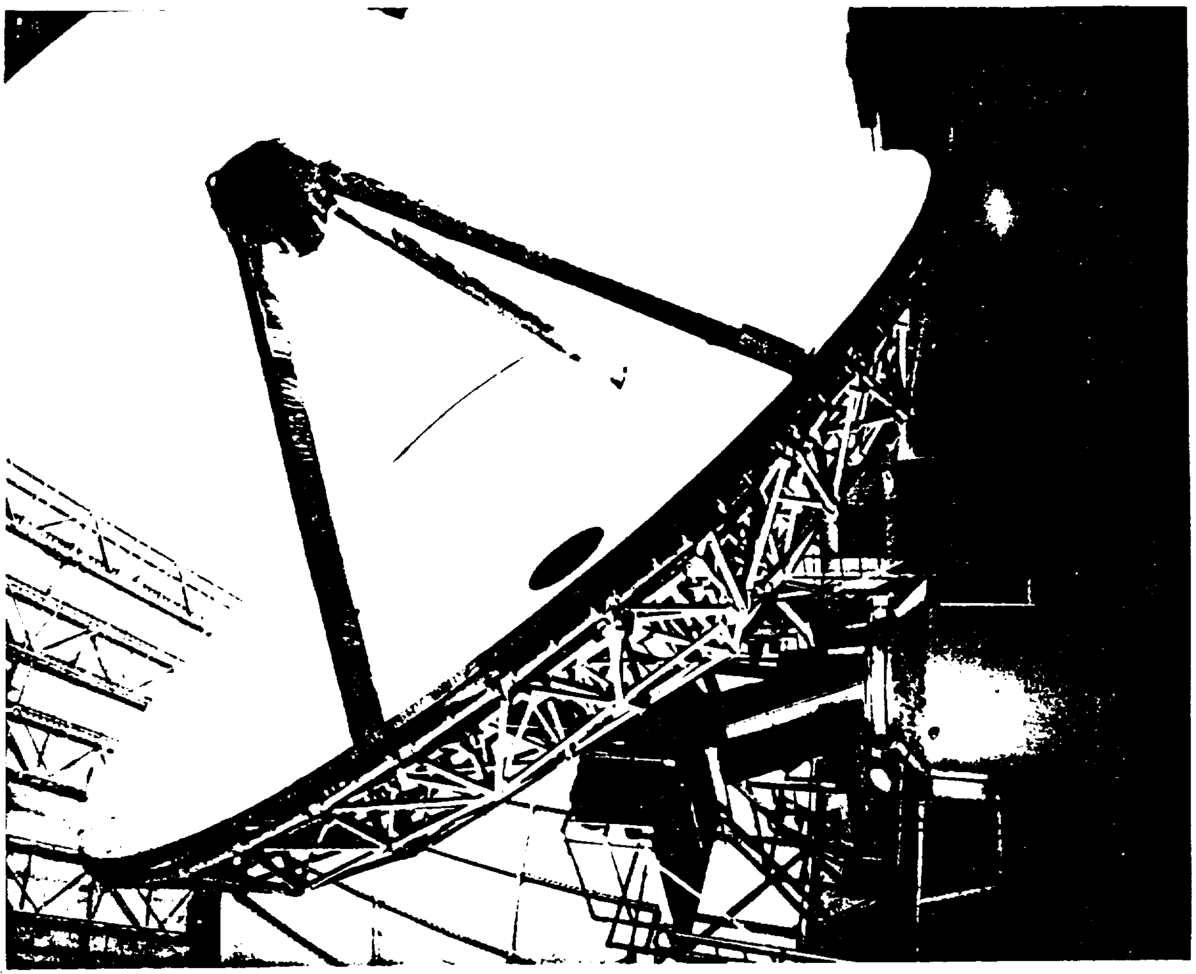


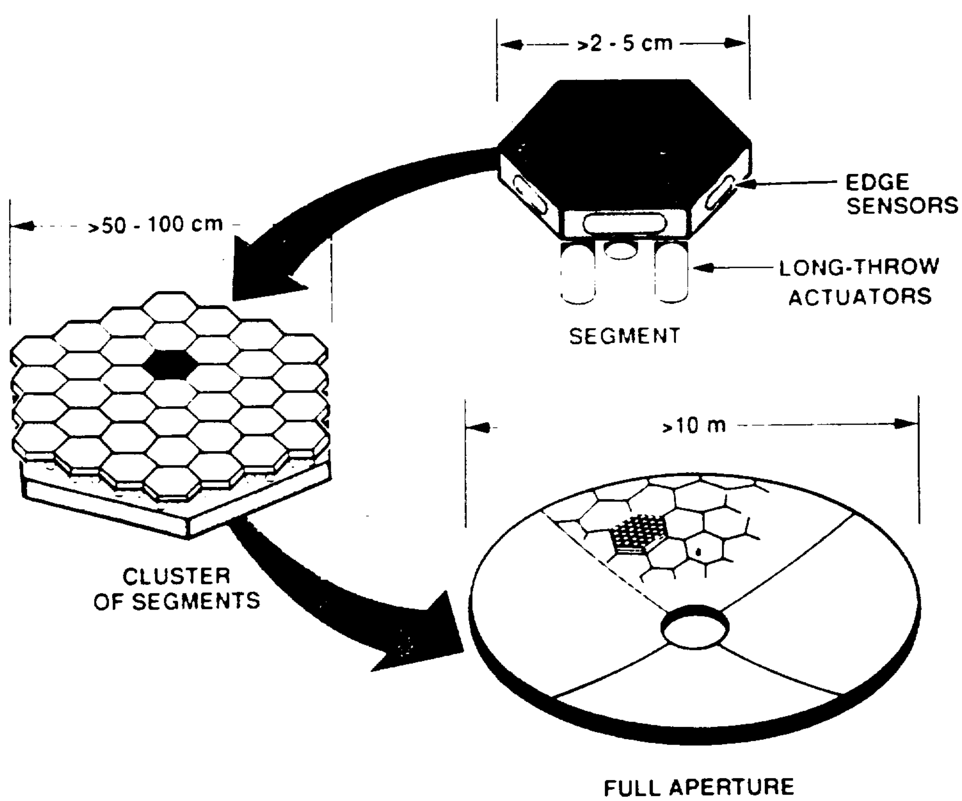
BASELINE RESULTS

STREHL RATIOS FOR
VARIOUS POWERS AND DIAMETERS

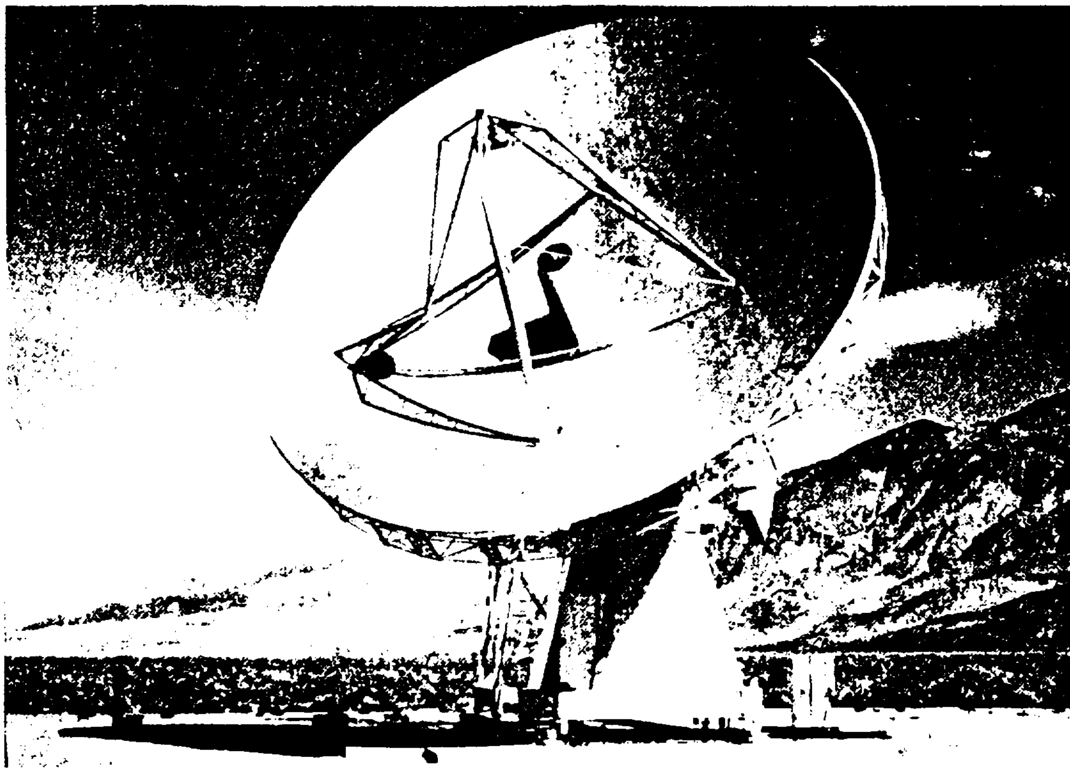
WITH TWO REALIZATIONS OF KOLMOGOROV FLUCTUATIONS

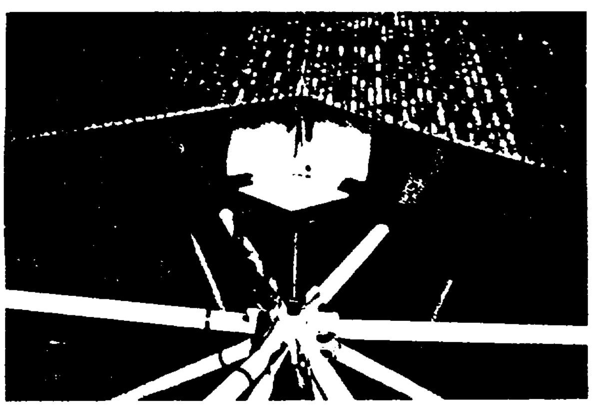


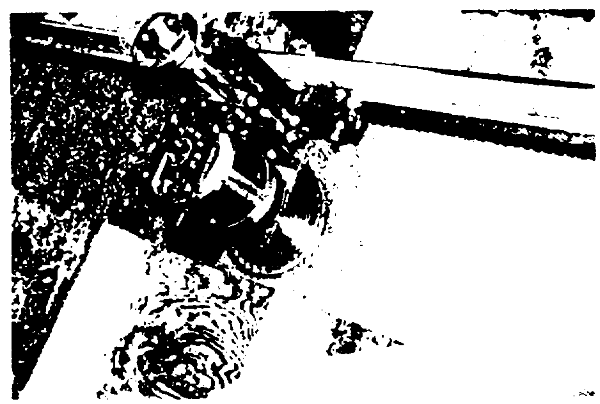


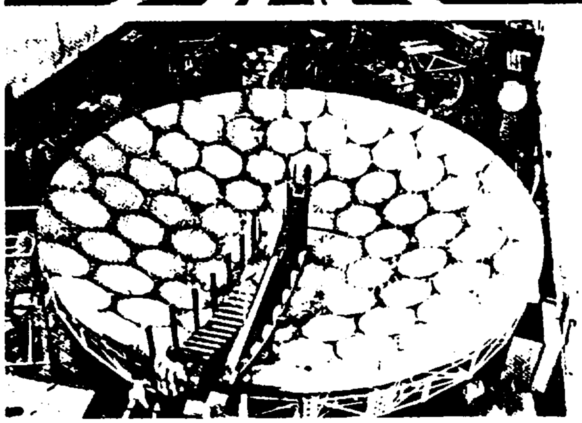

>2 - 5 cm
EDGE SENSORS
LONG-THROW ACTUATORS
SEGMENT
>50 - 100 cm
CLUSTER OF SEGMENTS
>10 m
FULL APERTURE

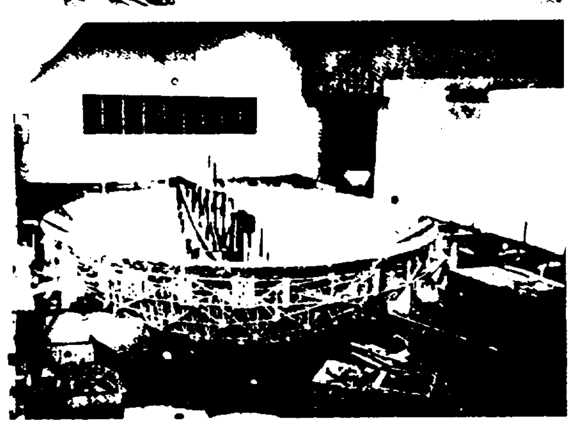
1

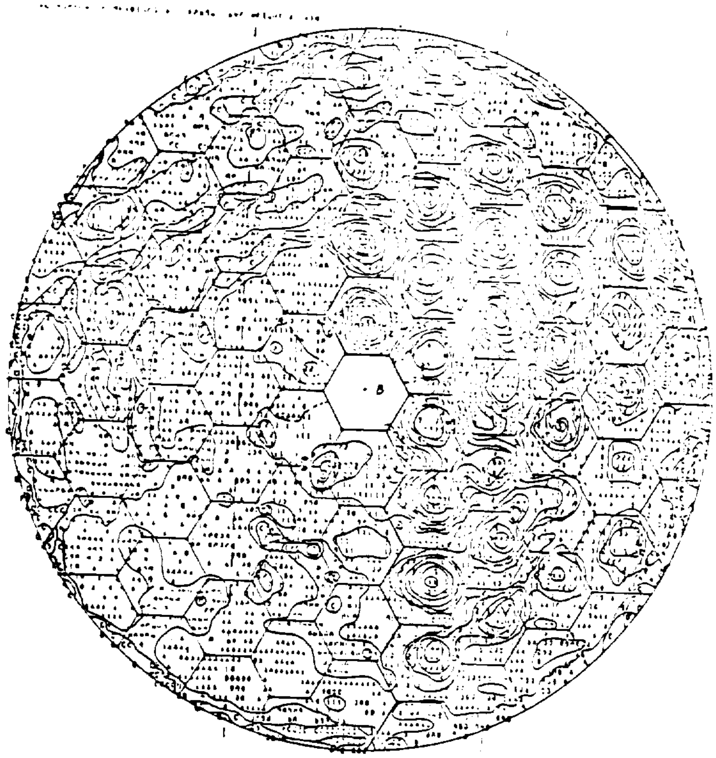








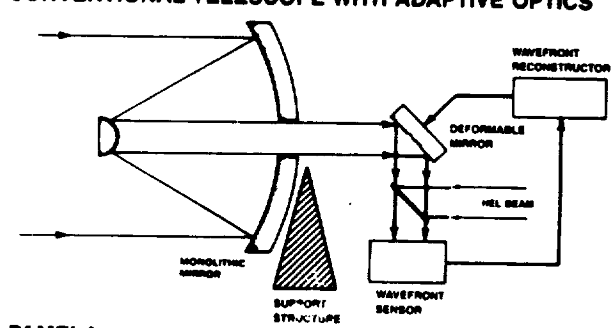




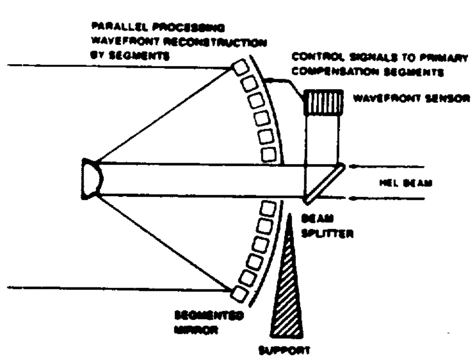
Computer map of prototype dish surface as measured following the initial remounting of the panels. Approximate boundaries of the panels are drawn in, and approximate, hand-drawn contours are shown. Positive heights above a best-fit paraboloid are indicated by the digits 0-9, negative heights by the letters A-I, in 25 um (0.001 inch) steps. If a given point does not fall within ± 1/4 unit of an integer value, a blank is printed. The panels to the left of the heavy jagged line had "stretchers" attached and those to the right did not (see text). Note the obvious "crowning" of the unstretched panels as compared with the stretched ones. The rms surface errors for the two areas are 30 um and 60 um respectively, and the mean value is 50 um.

PAMELA — A Lower Cost Approach

CONVENTIONAL TELESCOPE WITH ADAPTIVE OPTICS



PAMELA

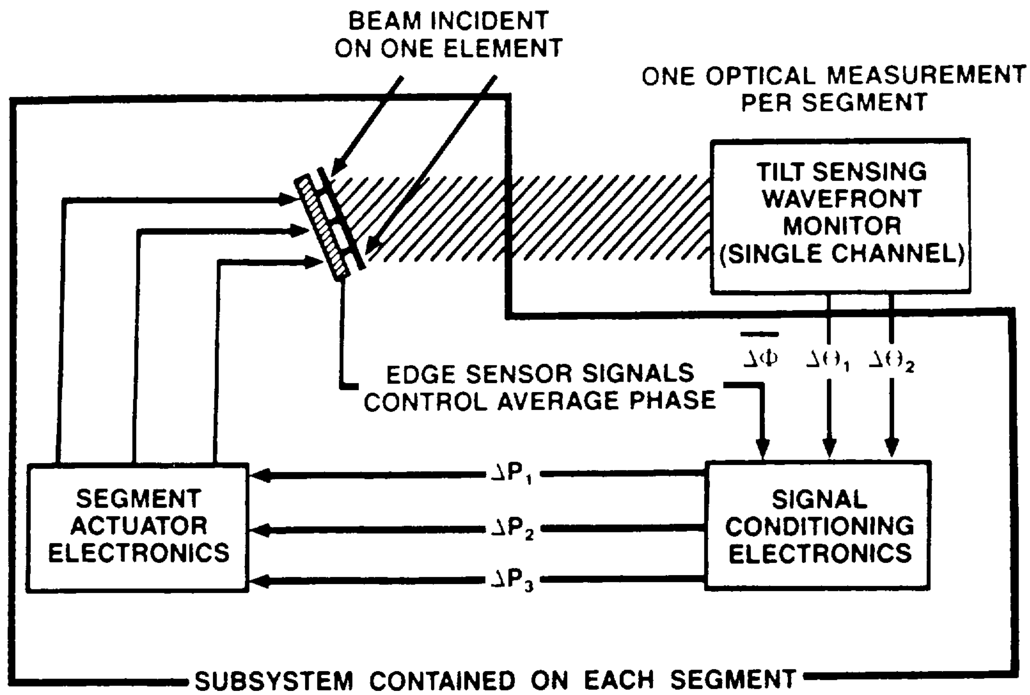


	CONVENTIONAL ADAPTIVE OPTICS	PAMELA
PRIMARY	● MONOLITHIC OR LARGE SEGMENTS	○ MASS PRODUCED SEGMENTS
SECONDARY	●	○
SUPPORT STRUCTURE	●	○
WAVEFRONT SENSOR	●	○
WAVEFRONT RECONSTRUCTOR	●	○ NOT REQUIRED
CONTROL PROCESSOR	● MULTI CHANNEL	○ ON ARRAY or ROM ON SEGMENT
COMPENSATION MIRROR	● HIGH DENSITY MEMBRANE OR SEGMENTS	○ ACTUATORS ONLY

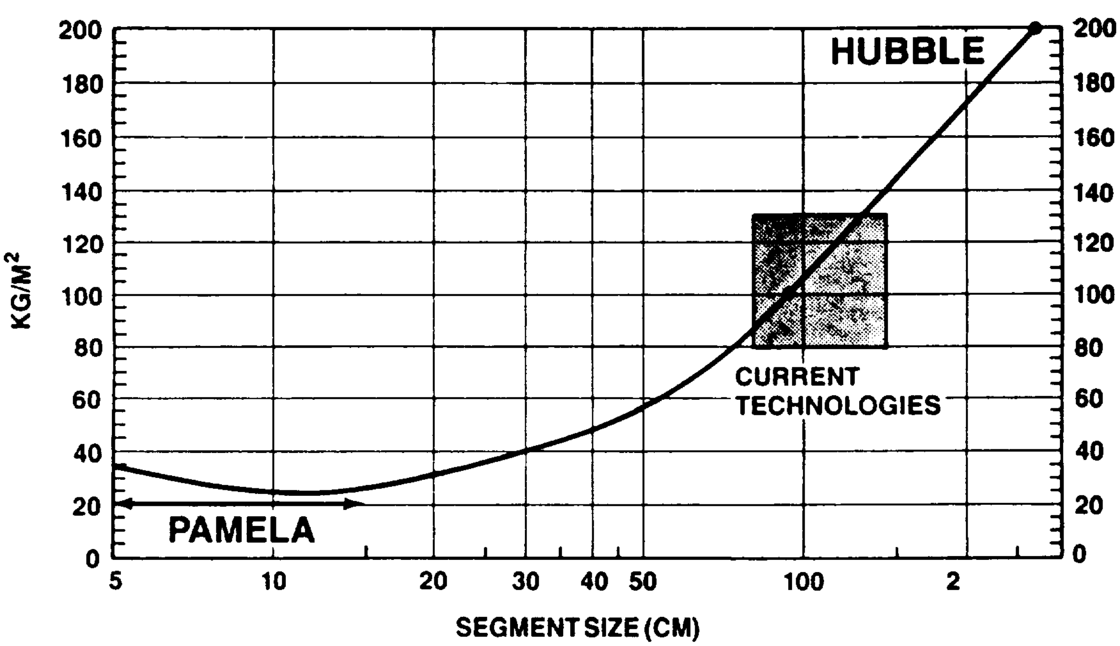
● HIGH COST

○ LOW COST

TTPM FUNCTIONAL BLOCK DIAGRAM



MIRROR AREAL MASS DENSITIES AS A FUNCTION OF SEGMENT SIZE



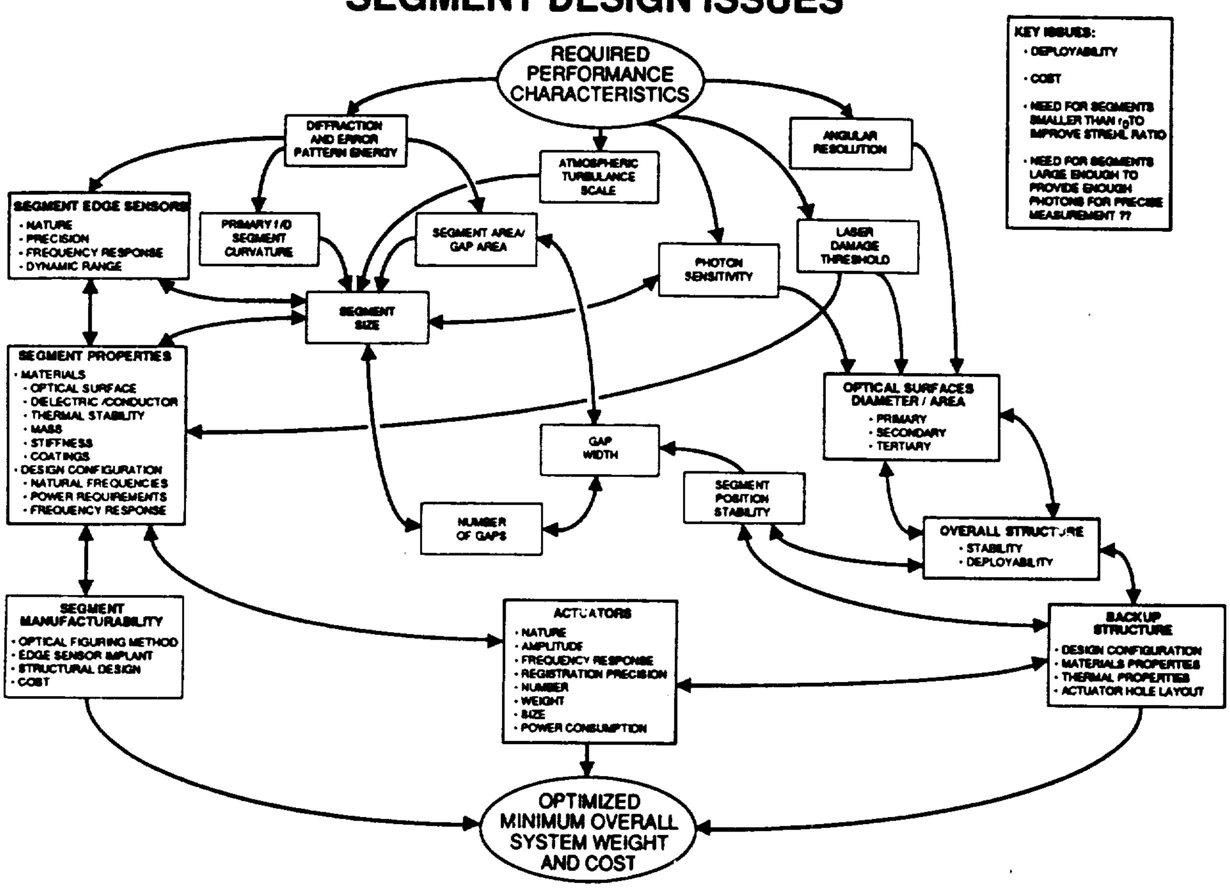
CONSTRAINTS AFFECTING SEGMENT SIZE

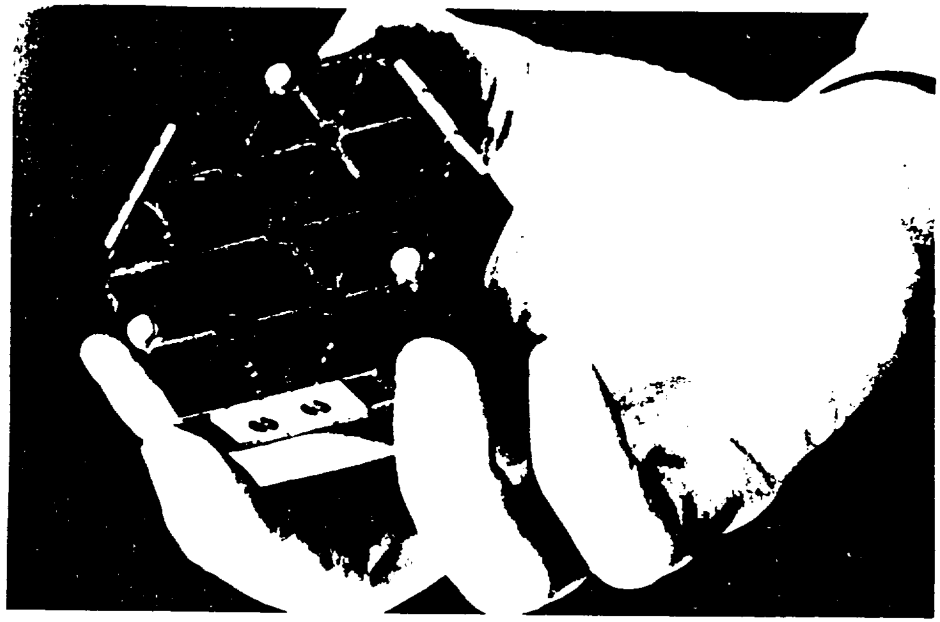
WHAT DETERMINES THE PHASED ARRAY ELEMENT SIZE ?

- UPPER LIMIT
  - SCALE SIZE OF OPTICAL DISTURBANCES
    - VIBRATION-INDUCED DISTURBANCES
    - ATMOSPHERIC DISTURBANCE SCALE
    - THERMAL INERTIA

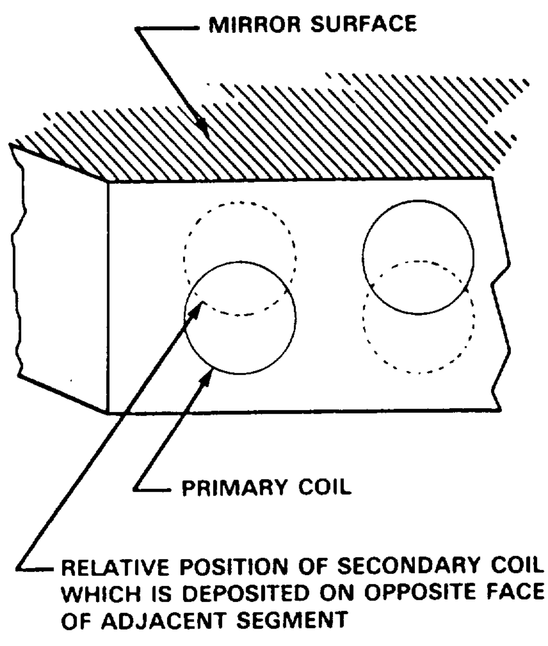
- LOWER LIMIT
  - SEGMENT FABRICATION COSTS
  - ACTUATOR STROKE
  - SYSTEM WEIGHT
  - SYSTEM COMPLEXITY

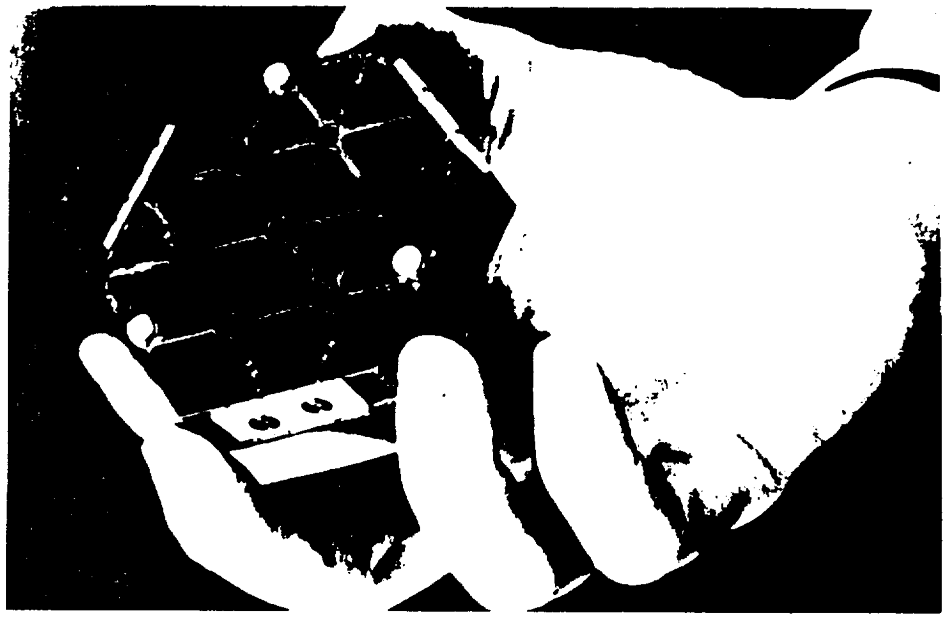
SEGMENT DESIGN ISSUES



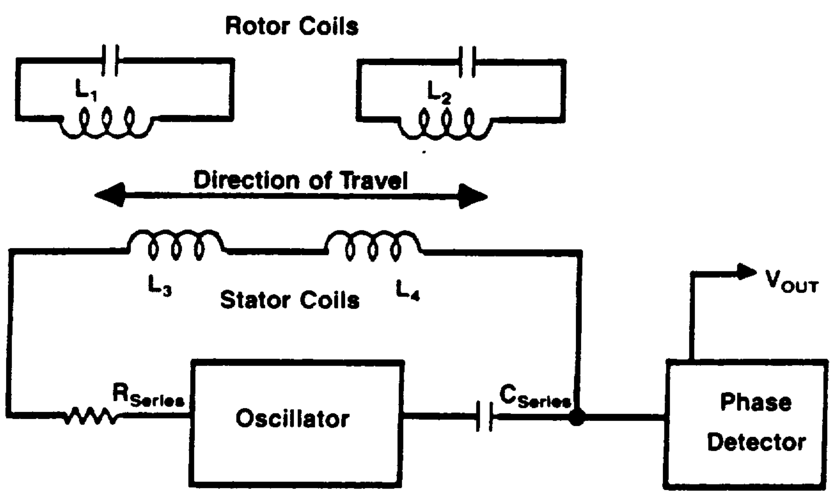


ARRANGEMENT OF SENSING COILS ON SEGMENT EDGE

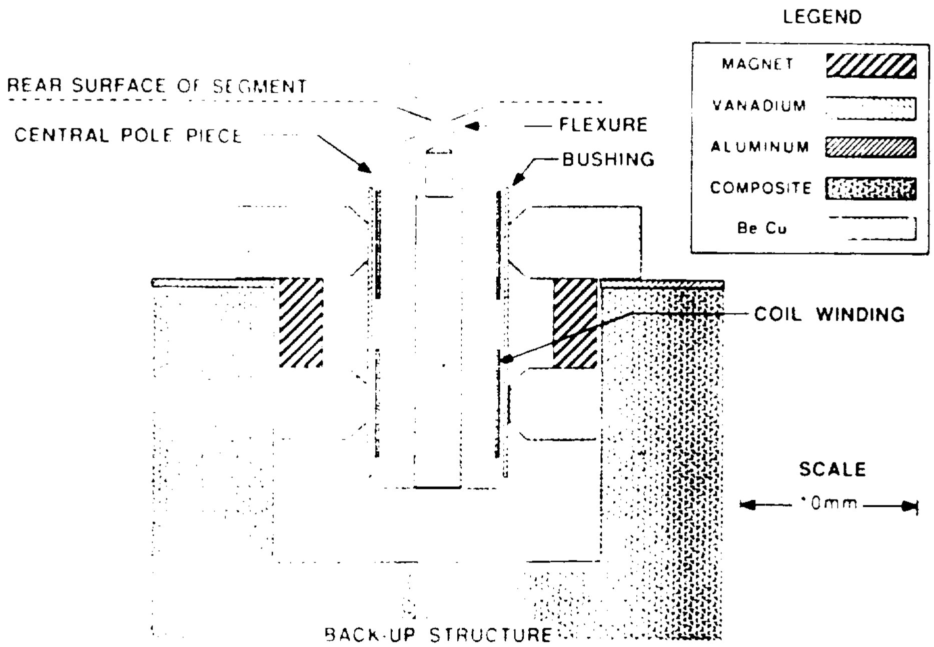




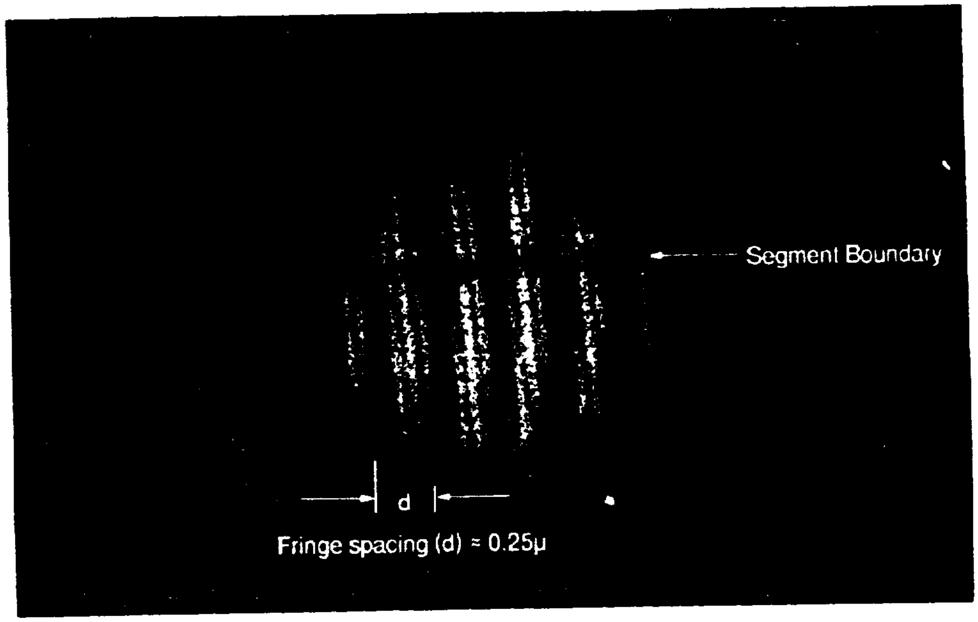
Edge-Matching Sensor Circuit Diagram



ACTUATOR DETAIL



WHITE LIGHT FRINGES



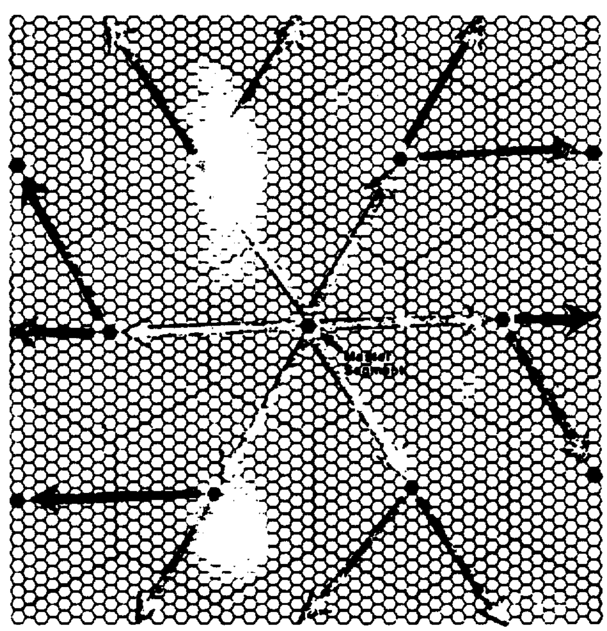
STEPS IN RAPID CONVERGENCE ALGORITHM

- EDGE MATCH ALL SEGMENTS
- MEASURE TILTS OF ALL SEGMENTS
- APPLY AND FIX SEGMENT TILTS WHILE EDGE MATCHING
- COMPUTE PISTONS OF ALL REFERENCE SEGMENTS AT CENTER OF EACH CLUSTER BY INTEGRATING TILTS ALONG SPECIFIED PATHWAYS (RELATIVE TO MASTER SEGMENT)
- ADJUST AND FIX PISTONS OF REFERENCE SEGMENTS AT CENTER OF EACH CLUSTER
- PISTONS OF REMAINING SEGMENTS WITHIN EACH CLUSTER ARE ADJUSTED BY EDGE MATCHING TO REFERENCE SEGMENT

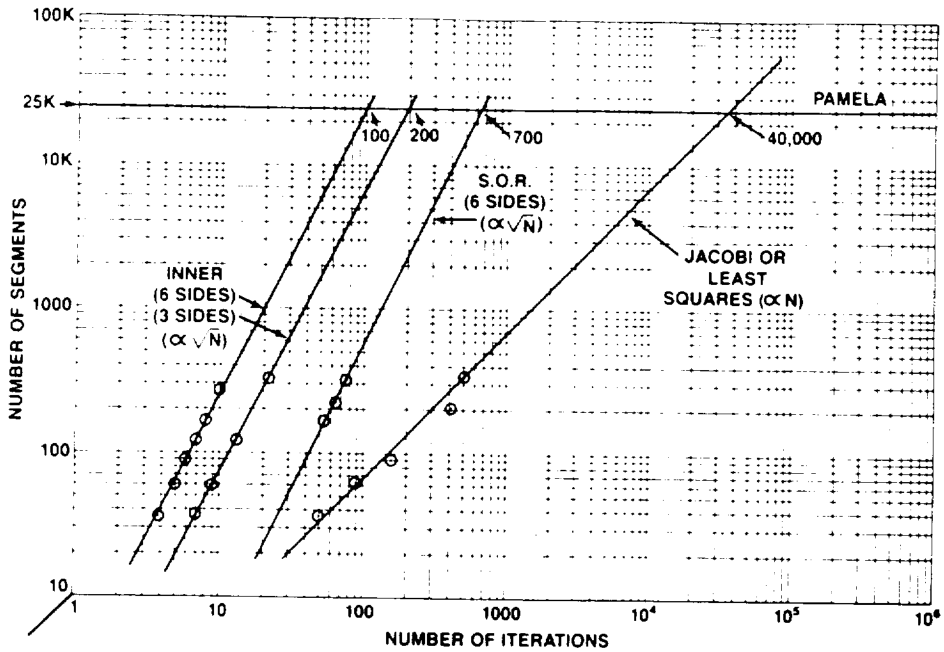
⬢ REFERENCE SEGMENTS

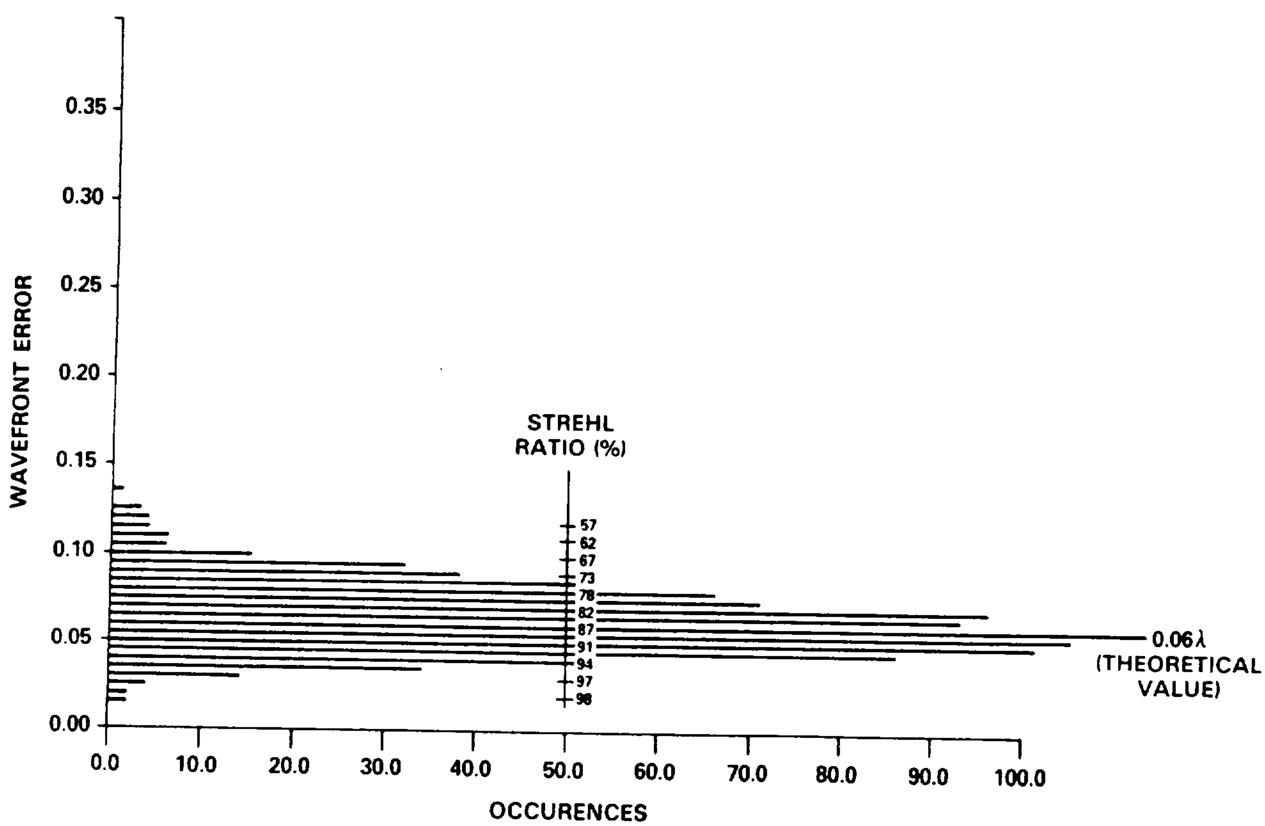
⬡ DEFINES CLUSTERS

→ POSSIBLE PATHWAYS OF PISTON COMPUTATION



SURFACE SETTING ALGORITHMS
STEP FUNCTION RESPONSE (CONVERGENCE TIME)

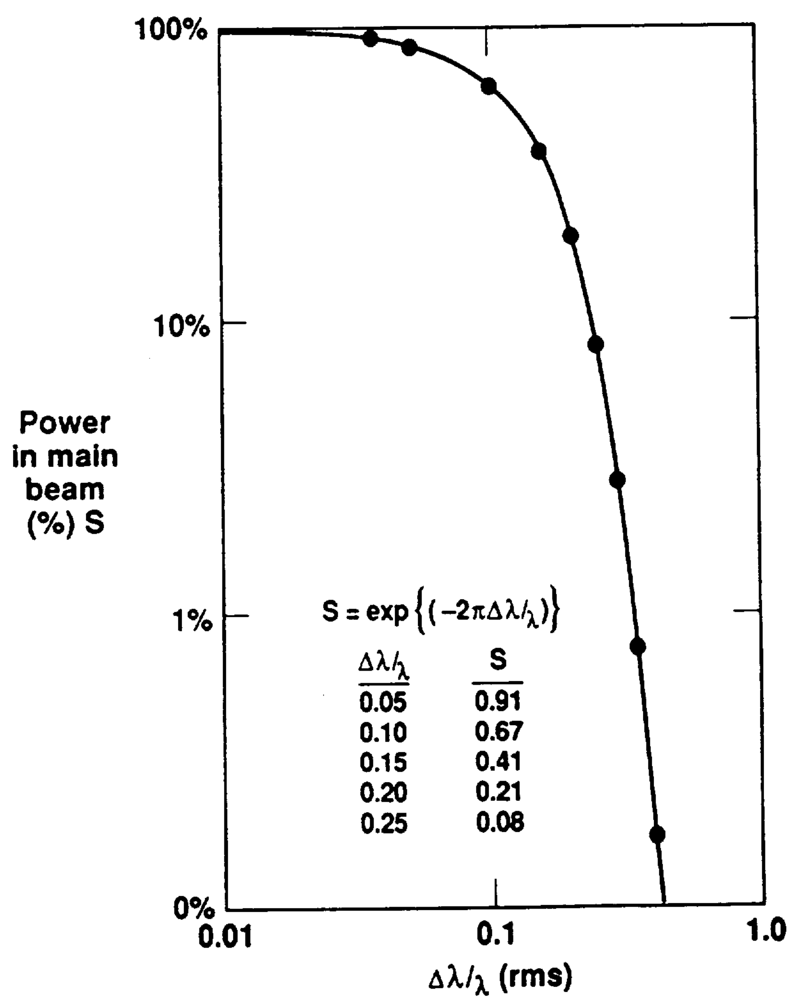


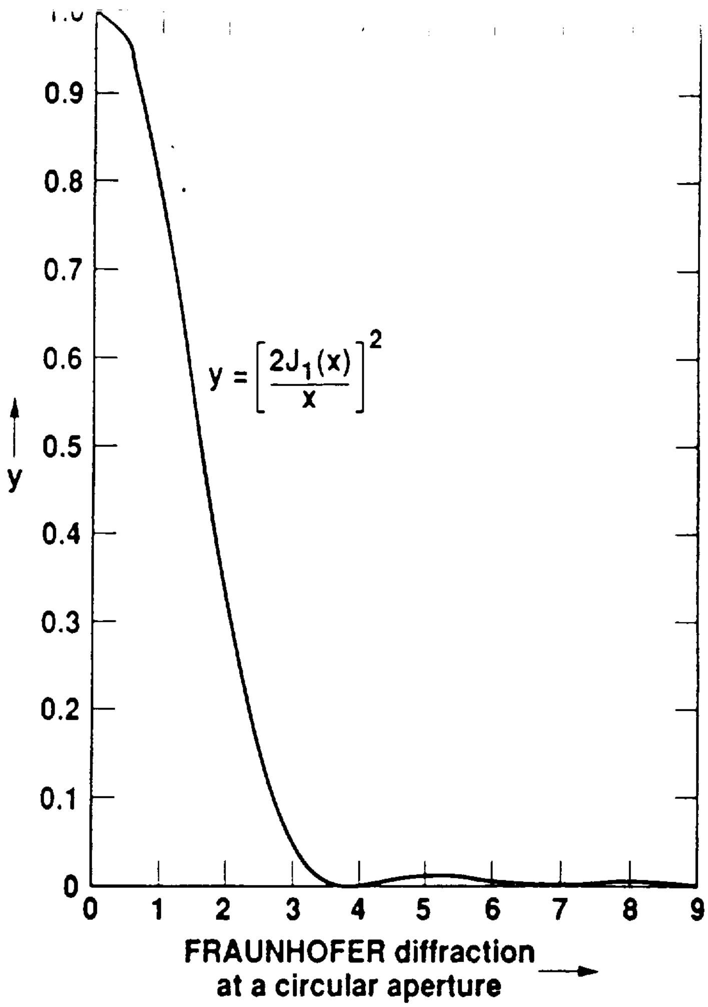


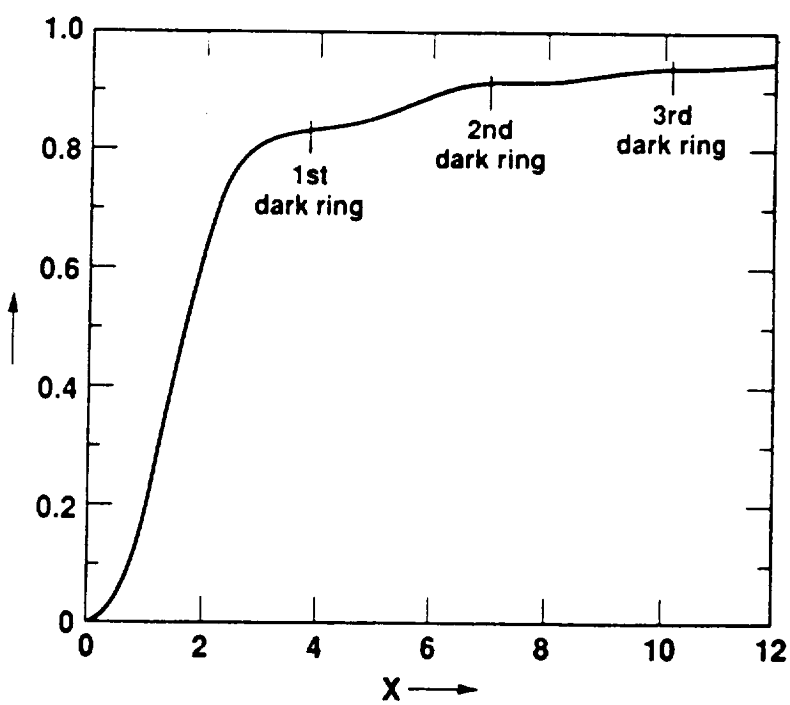
The integrated control concept is scalable

- Simple sensor arrays
  - CCDs
  - Quad cell witness plate
- Linear distribution of sensor data to segments
- "Smart" self-processing segments
- Long stroke actuators
- Only parallel processing required

Strehl ratio

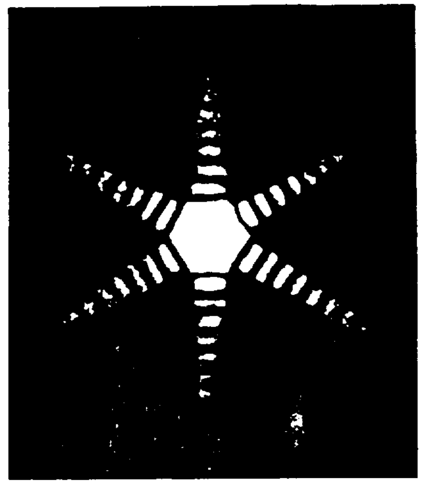




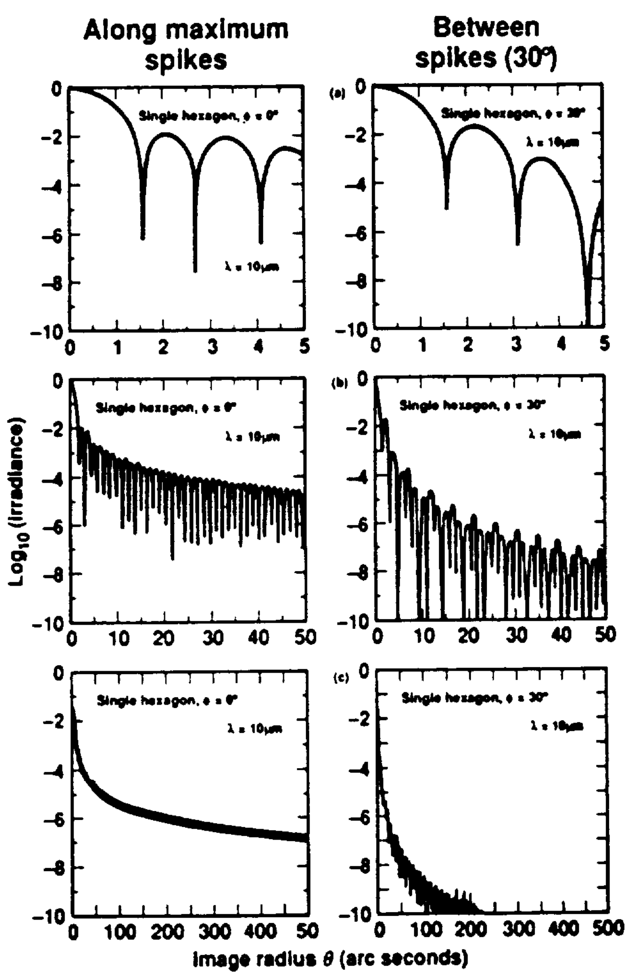


The function $1 - J_0^2(x) - J_1^2(x)$ representing the fraction of the total energy contained within circles of prescribed radii in the FRAUNHOFER diffraction pattern of a circular aperture.

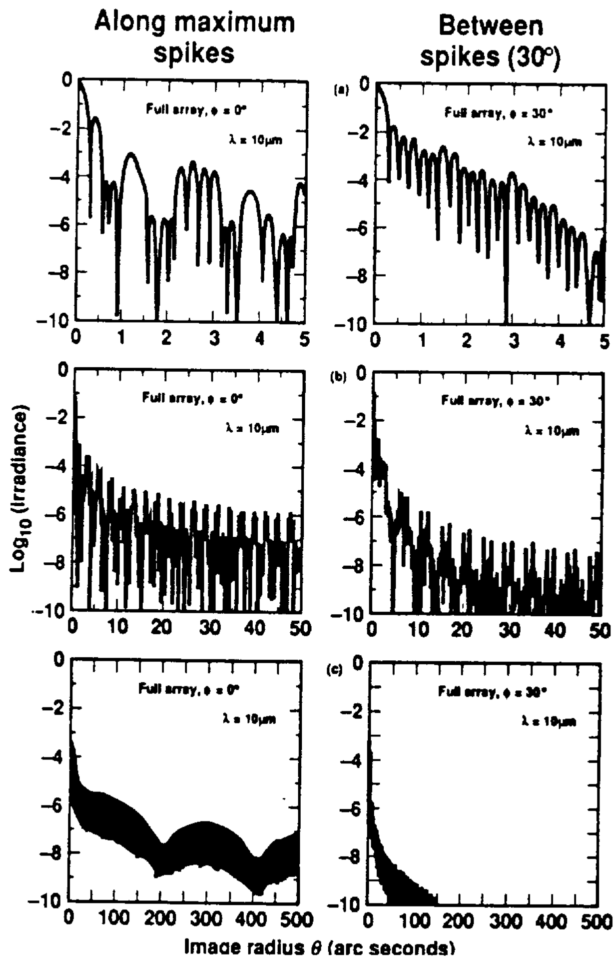
DIFFRACTION PATTERN FROM A SINGLE HEXAGONAL MIRROR



Single hexagon diffraction pattern at 10 micron wavelength (1.8-meter hexagons)



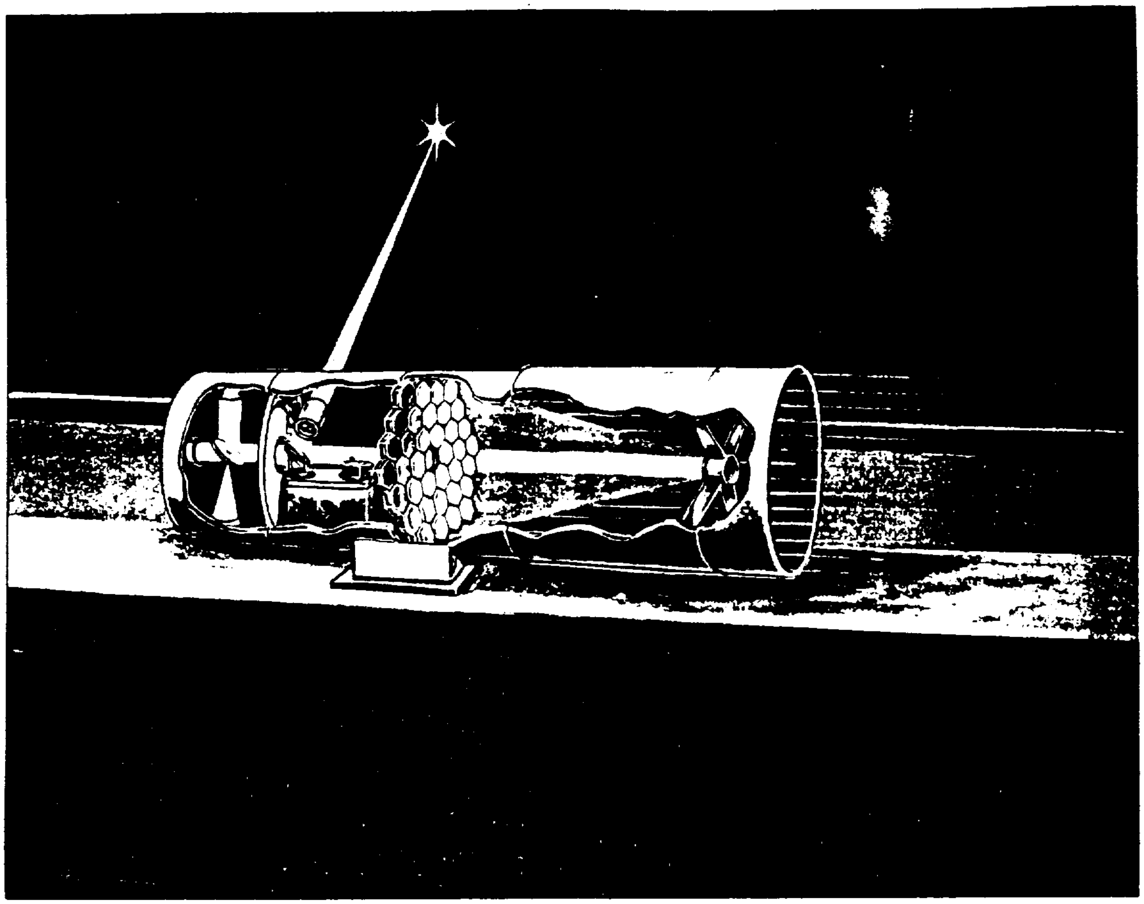
36-hexagon diffraction pattern at 10-micron wavelength (1.8-meter hexagon—10-meter full aperture)



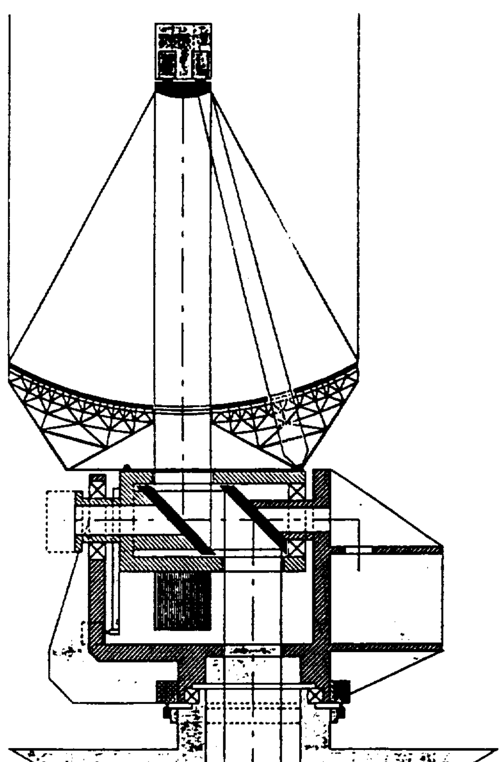
Effect of segmentation on aperture performance

- Strehl does not depend on segment number
- Strehl degradation depends on percentage area of gaps to total area:
  - Gap 1% of segment area → Strehl = 96%
  - Gap 0.65% of segment area (Keck design) ——→ Strehl = 97.4%
- Variation in diffraction pattern at levels of 10^{-5} of peak and less and are present only many airy diameters away
- Details of energy distribution within the central lobe are unaffected by segmentation

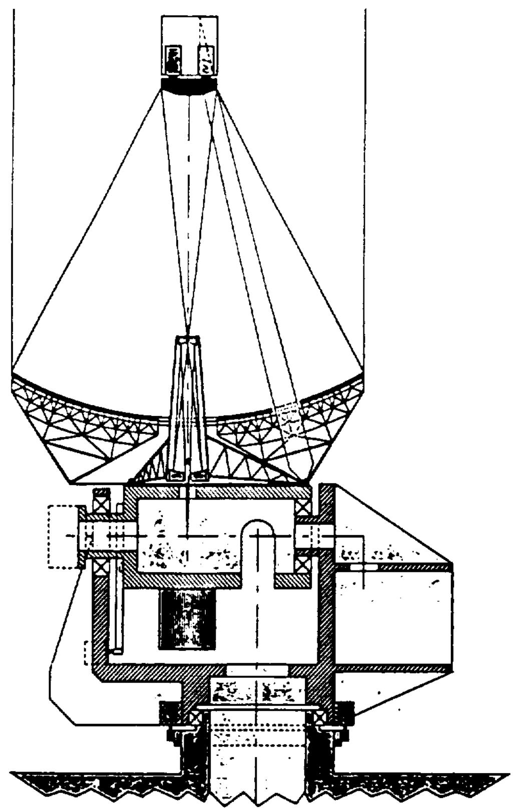
Imaging performance is not affected by segmentation



PAMELA Ground-based Laser Beam Director



ORIGINAL PAGE IS
OF POOR QUALITY

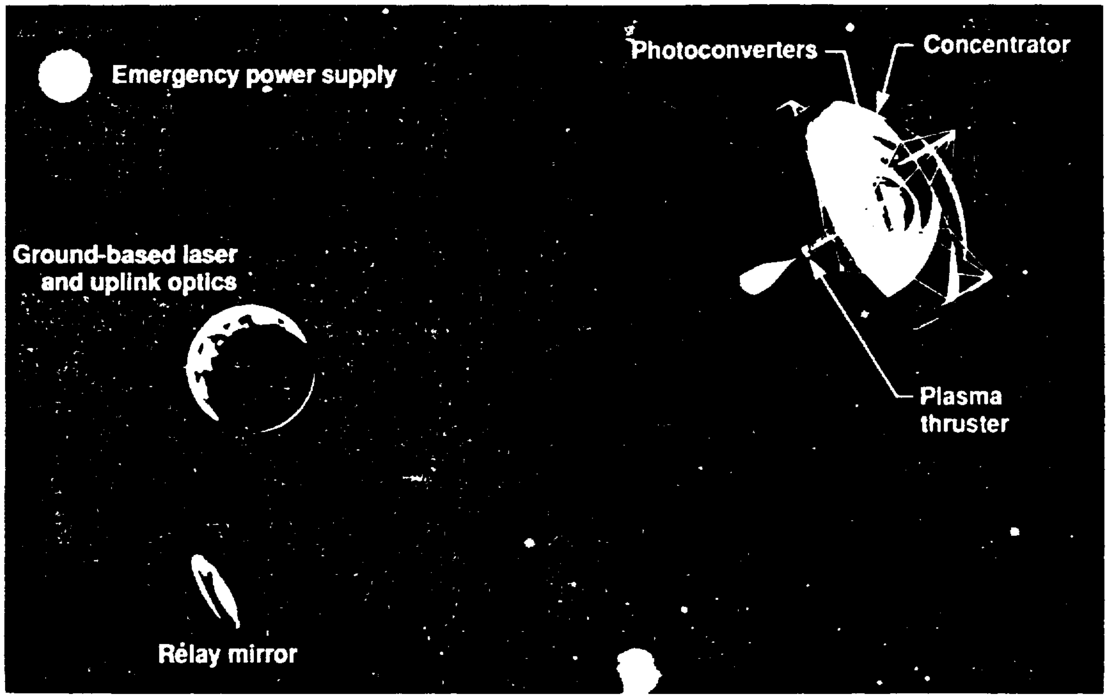


Technological goals of PAMELA-Type Optical System

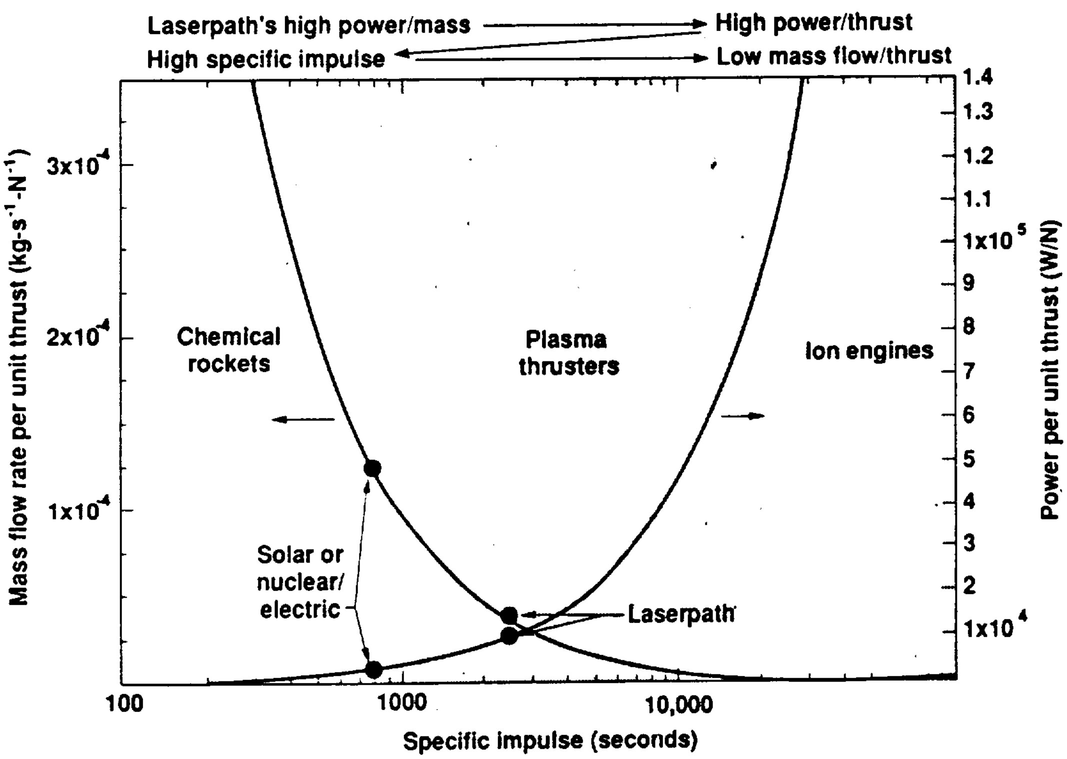
- Very large apertures (>10 m)
- Fast primary optic for a compact, lightweight telescope
- Compensation for internal optical aberrations
- Compensation for atmospheric turbulence
- Control architecture scalable to very large numbers of segments
- Elimination of the requirement to reconstruct wavefront phase from gradient measurements
- Large adaptive optics closed-loop bandwidth
- Diffraction-limited beam quality
- Identical intelligent mirror segments
- Identical wavefront sensor modules
- Economical fabrication through mass-production methods

Laserpath is a ground-based laser-driven space power and propulsion concept

A Laserpath manned lunar shuttle (MLS) departing for the moon

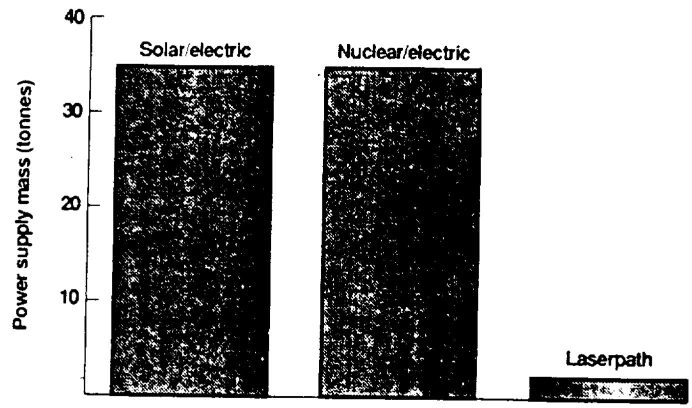


Because laserpath can exploit the high specific impulse of plasma thrusters, it requires little propellant mass



Laserpath's power supply mass is low in comparison with nuclear or solar vehicles for three reasons:

- The prime power source is not on board
- Monochromatic laser light is converted to electric power with high efficiency
- Pulse repetition rate matching of laser and plasma thrusters reduces need for on board power conditioning equipment



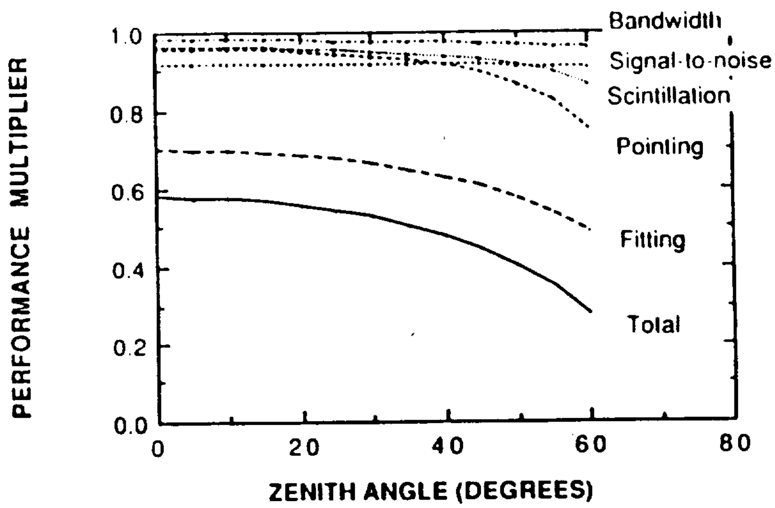
Shuttle rendezvous with tugboat in LEO. Residual shuttle main tank fuel is transferred to tug. Tug then boosts main tank or full shuttle payload to GEO

• I_{sp} = 1,500 seconds	
• ΔV = 5,630 meters/sec (each way)	
• Tug spacecraft dry mass	= 4,400 kg
• Available fuel mass	3,640 kg*
• Main tank dry mass (or alt. payload)	= 32,300 kg
• Total required energy	= 4,500 GJ
• Minimum one way mission duration	= 5.2 days
• Minimun required laser power	= 10.2 MW

* 520 kg H_2 3, 120 kg LOX

ADAPTIVE OPTICS ERROR BUDGET

λ = 1μm, r_0 = 9.6 cm AND θ_0 = 15 μrad AT ZENITH,
ACTUATOR SPACING 10cm, BANDWIDTH 100 Hz, WIND 6 m/s,
RETRO ARRAY AT MEAN POINT-AHEAD LOCATION



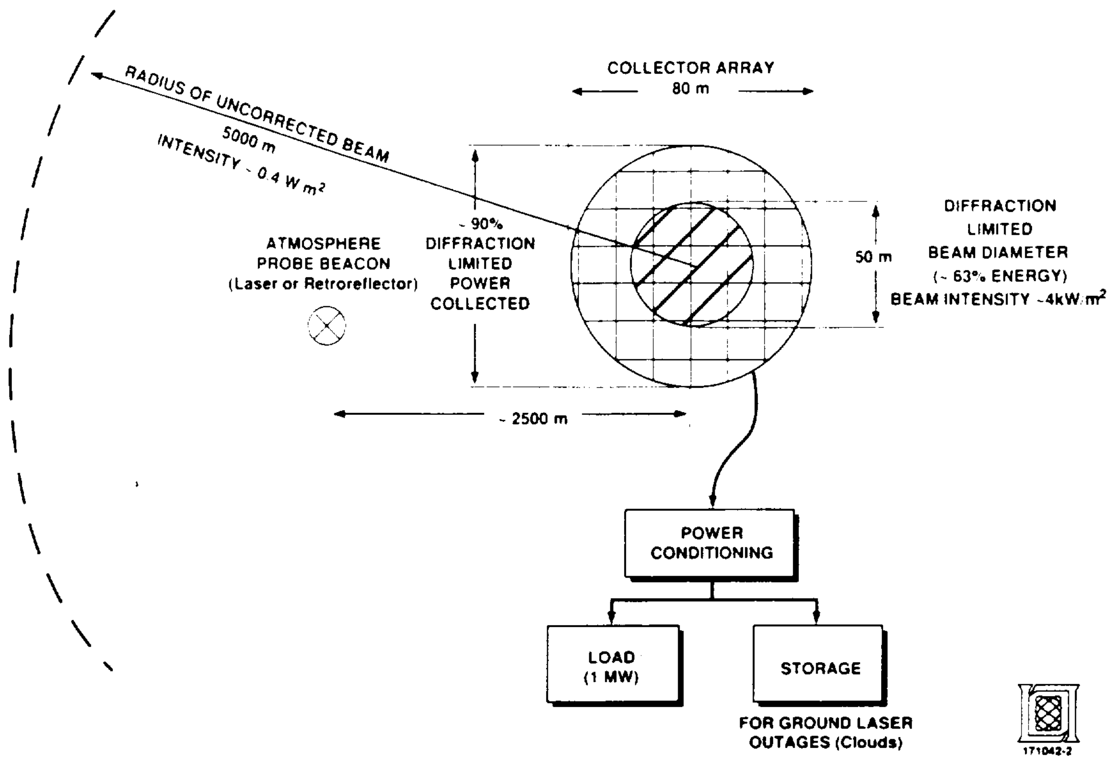
BASELINE SELENE POWER SYSTEM

REPRESENTATIVE POWER BUDGET

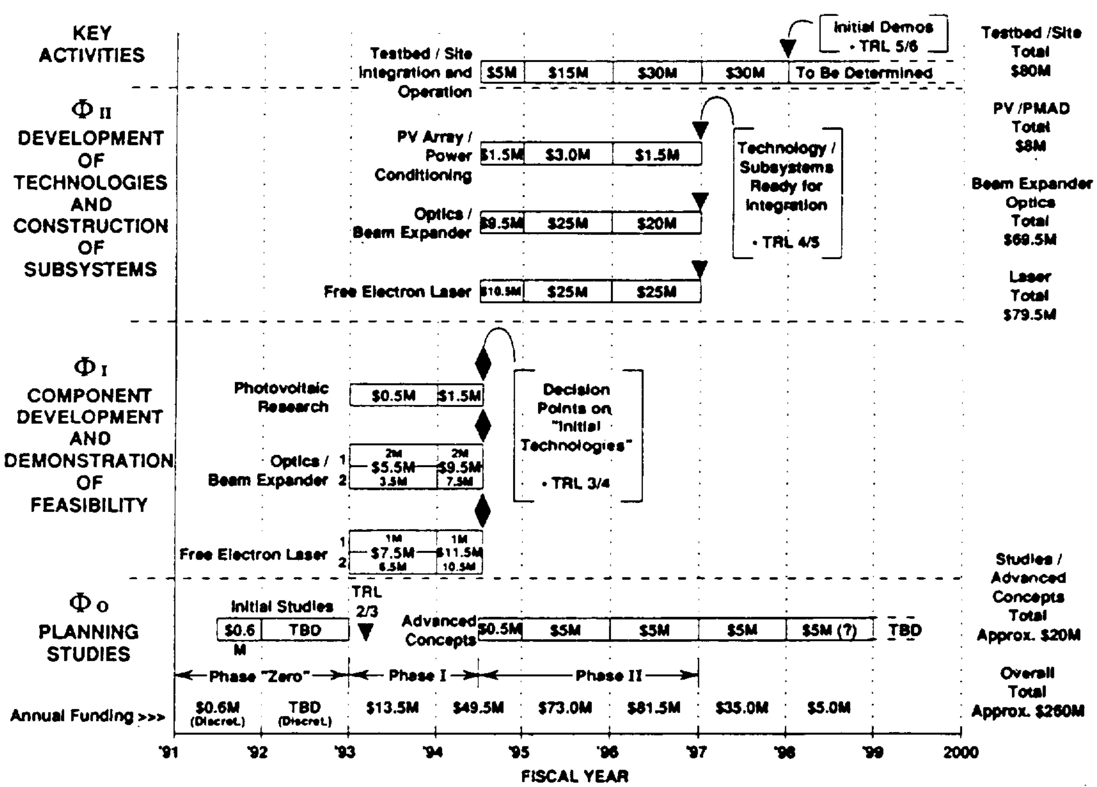
	POWER	EFF.
EARTH SITE POWER INPUT	110 MW	
LASER EFFICIENCY		0.1x
LASER OUTPUT	11 MW	
OPTICS TRANSMISSION		0.9
POWER OUT OF APERTURE	10 MW	
ATMOSPHERIC TRANSMISSION		0.9
ATMOSPHERIC COMPENSATION		0.5
COLLECTOR GEOM. EFFICIENCY		0.9
ARRAY ELECTRICAL EFFICIENCY		0.5
NET PV ARRAY ELECTRICAL POWER OUTPUT TO USER	2 MW	

A MINIMUM OF 3 EARTH STATIONS IS REQUIRED TO PROVIDE CONTINUOUS 1+ MEGAWATT ELECTRICAL POWER TO USERS ON MOON

LUNAR STATION



PROJECT SELENE



LASER POWER BEAMING -- PROJECTION OF EXPENDITURES

Years: '93 | '94 | '95 | '96 | '97 | '98

Technology Area	Funding ('93 – '98)	Performer / Activity
• Free Electron Laser Option I - RF FEL	1.0M, 1.0M	*(Industry)* Track parallel DoD RF FEL and generate alternate NASA Concept. This work will terminate in mid-'94 if Option II succeeds.
• Free Electron Laser Option II - Induction FEL	6.5M, 10.5M	*(Industry)* Build and test new high gradient induction accelerator. *(LLNL)* Model FEL. ◆ Decision point for initial technologies (TRL 3/4)
• Option II (Cont'd)	10.5M, 25M, 25M	*(Industry/MSFC)* Construct/ Test Induction FEL. ◆ Technology/Subsystem ready for integration (TRL 4/5)
• Optics/Beam Expander - Option I Monolith Primary/ Membrane AO	2M, 2M	*(MIT Lincoln Lab)* Track Parallel DoD optics and generate alternate NASA Concept. This work will terminate in mid-'94 if option II succeeds.
• Optics/Beam Expander Option II - Segmented Primary AO	3.5M, 7.5M	*(JPL/LLNL/MSFC/Industry)* Design and test mass-produceable precision segments. Design beam expander and control system
• Option II (Cont'd)	9.5M, 25M, 20M	*(JPL/MSFC/Industry)* Produce segments. Build telescope for subsystem.
• Photovoltaic Research/ PV Array + Power Conditioning	0.5M, 1.5M, 1.5M, 3.0M, 1.5M	*(JPL/LeRC/Industry)* Develop efficient PV power converter. ◆ Initial Demonstration (TRL 5/6)
• Testbed/Site Integration and Operation	5M, 15M, 30M, 30M, TBD	*(MSFC/JPL/Lincoln Lab)* Integrate Laser Beam Expander and PV Array and Test.
• Advanced Concepts	0.5M, 5M, 5M, 5M, 5M	*(NASA Centers/HQ)* Applications/Mission Studies
Annual Funding	13.5M, 49.5M, 73M, 81.5M, 35M, 5M	

LASER POWER BEAMING POWER AND PROPULSION FLIGHT DEMONSTRATION

- **LASER-ELECTRIC PROPULSION VEHICLE FLIGHT FROM LOW EARTH ORBIT (LEO) TO LOW LUNAR ORBIT (LLO)**
  - **MISSION WOULD DEMONSTRATE/INVESTIGATE:**
    - **LASER POWER TRANSMISSION THROUGH ATMOSPHERE**
    - **TRACKING OF REMOTE TARGET BY TRANSMITTER AND RECEIVER**
    - **POWER CONVERSION BY PHOTOVOLTAIC ARRAY**
    - **RADIATION IMPACTS TO PV ARRAYS DUE TO TRANSFER THROUGH VAN ALLEN BELTS**
    - **ELECTRIC PROPULSION SYSTEM AS MISSION POWER LOAD**
    - **INTERACTIONS BETWEEN ELECTRIC PROPULSION SYSTEM AND PV ARRAYS**
  - **OTHER FEATURES OF THE DEMO MISSION:**
    - **OPERATE AT MODEST POWERS (10's OF kW TO MW)**
    - **INITIAL DEMO FROM LEO TO HIGH EARTH ORBIT (GEO ?) TO INVESTIGATE VAN ALLEN BELT IMPACTS CAN BE DONE WITH FIRST GENERATION SMALL TRANSMITTER MIRROR.**
    - **SECOND GENERATION LARGER TRANSMITTER USED FOR TRANSFER TO LLO**